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ABSTRACT

Presented is a technical physics module designed to meet objectives in electricity and magnetism for students in an introductory physics course and emphasizing laboratory work. Included are basic text materials, prerequisites, objectives, a posttest, experiments, and a teacher's guide. The module is designed to be used on an individual instruction basis or to be supplemented with lectures. The text consists of six sections: (1) introduction, (2) electric current, (3) electromagnetic induction, (4) capacitance, (5) transient currents, and (6) other physical principles important to the ignition system. Five experiments are also included in the text. (HM)

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THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

Unit 4A OF

A MODULAR APPROACH TO PHYSICS FOR TECHNICIANS

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TEACHER'S GUIDE
FOR
THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

I. *Introduction to the Concept of a "Module"*

Textbooks have fundamental disadvantages in physics for technology. Programs vary too greatly from college to college. Even at a given institution, needs of students are different for the different technologies. Learning materials in "technical physics" need a strong laboratory emphasis, and they should be systems oriented.*

A *Module* of instructional material contains:

1. Behavioral objectives for the unit, stated as goals to which the student will work.
2. An entry test for the unit based on prerequisites, or a statement of prerequisites. A student lacking prerequisites should be referred to developmental or remedial materials.
3. An instructional program consisting of
    a. a mechanical, electrical, or natural system generally familiar to the student, available in the laboratory, and around which the module is to be built (e.g. binoculars; incandescent lamp; ignition system of an automobile).
    b. a description of what the student is to do with the system of (a) in order to meet the objectives of (1). This description, augmented with information, may be presented to the student through printed material, film or film loops, audio tape, video tape, or any

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*Bill G. Aldridge, *The Physics Teacher*, Volume 8, Number 6, pp 302-322, September 1970.

other appropriate medium. The description and information could take the form of narration, questions or problems, or laboratory activities involving measurement and experimentation.

4. An exit test for the module based on the objectives of (1).
5. A resource document for the teacher. This document describes the module in terms of its prerequisites, objectives, and the detailed system needed in the laboratory and where it can be purchased, or how it can be assembled from components, with similar information on remedial or developmental materials, printed materials, and the various media. It would include keys for entry and exit tests, suggestions for use of media and laboratory apparatus, and discussions of questions, problems, and laboratory activities in the unit.

A given module forms approximately two or three weeks of instruction in "technical physics". Because a teacher creates his own "course" by selecting appropriate modules, there should be available at least twice as many modules as would be used in a given course. This requirement places the number needed at between 20 and 40 modules for a one year course in technical physics.

A course created by the teacher with modules will not proceed in a logical order. Instead, each module will give a distribution of coverage over several topics, the distribution being peaked at a particular topic. After students have studied physics through a set of modules, the distributions overlap in such a way that all major topics in physics will have been "covered" as if the course had been taught in the traditionally logical fashion. However, because of the overlap of the modules, there is greater repetition of topics in different circumstances, giving the student the repertoire of specifics leading him to form generalizations.

It is important that the use of systems in physics be distinct from the use of the *same* or similar systems in technology courses. In physics such systems serve mainly to motivate investigations of fundamental principles by having the student go from something specific and familiar to something more general or less familiar, but related. The physics objectives provide the key to the use of such systems and related physics apparatus. In order for physics not to duplicate what is done in technology courses, and to meet the responsibility of giving the student abilities and understandings of fundamental principles and concepts about physics which will serve him in his *career*, this procedure of going from the specific to the general and back to the specific must be followed carefully in the physics course.

II. *The Physics of the Automobile Ignition System Module*

This module is designed to meet some objectives in electricity and magnetism expected of students in an introductory physics course. Objectives are stated for certain definitions, laws and principles in electricity and magnetism. The following goals of the module are stated operationally in the student guide.

GOALS OF THE MODULE, PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

After completing this module, the student will:

1. be able to apply quantitatively, certain basic definitions in electricity and magnetism.
2. be able to apply quantitatively, certain principles and laws of electricity and magnetism.
3. be able to read and interpret graphs of electric and magnetic quantities.
4. be able to relate graphs of current versus time to appropriate circuit diagrams.
5. be able to calculate appropriate time constants of L-R, L-R-C, and L-C circuits.
6. be able to relate a graph of current versus time for an ignition system to the operation of various components of the system.

The module includes, in addition to basic text material, prerequisities, objectives, a post-test, experiments, and a Teacher's Guide. The module may be supplemented with lectures, or it may be used on an individual instruction basis. In either case, the instructor should be prepared to give special attention to the laboratory work, since the approach used is inductive. The following three and four week schedules are suggested:

THREE WEEK SCHEDULE

WEEK	*PAGES OF TEXT*	*EXPERIMENT*
1	1-23	1, 2
2	24-58 (up to *Transient Currents*)	3, 4
3	58-87	5

FOUR WEEK SCHEDULE

WEEK	*PAGES OF TEXT*	*EXPERIMENT*
1	1-19	1, 2
2	20-40	3, 4
3	41-67 (through problem 21)	5 pages 1-5
4	68-87	5 pages 6-9

III. *Experiments*

Most of the experiments for this module have been designed around equipment which is available in most community college physics laboratories. Experiments 1 and 5 have been written for an ignition system simulator (Sun). This device is now discontinued by the manufacturer, and many are available around the country. It can be duplicated simply with an automobile distributor driven by a motor (e.g. centrifigal force apparatus), along with a battery, spark plug, and associated wiring. A set up of this system need not cost more than 30-50 dollars.

If an ignition system is not possible for the lab, measurements can be taken directly off a system in a student's automobile.

A. *Experiment 1. An Examination of the Ignition System.*

This experiment has two major purposes: (1) to acquaint the student with the components of the ignition system; and (2) to give the student sufficient familiarity with the oscilloscope that he can make voltage and time measurements with it.

LIST OF EQUIPMENT

LISTED	*ALTERNATE*
12 V lead storage battery	Auto Ignition System
Sun Ignition Simulator	
Test Leads	
Oscilloscope	
Square Wave Oscillator	

B. *Experiment 2. The Relationship of Voltage to Current for a Conductor.*

The purpose of this experiment is for the student to arrive at Ohm's Law empirically. It also introduces the student to a simple electric circuit and the use of meters.

LIST OF EQUIPMENT

LISTED	*ALTERNATE*
Variable D.C. Power Supply	Battery and Rheostat
Double Pole-Double Throw Switch	
D.C. Voltmeter	
D.C. Milliameter	
Test Leads	
3 Test Resistors	

C. *Experiment 3. The Relationship of Resistance to Temperature for a Conductor.*

This experiment is designed as a measurement of the temperature coefficient of resistance, as well as teaching the principle of resistance increases with temperature for a conductor. This principle is basic to the operation of the ballast resistor.

LIST OF EQUIPMENT

LISTED	*ALTERNATE*
Slide Wire Wheatstone Bridge	
Test Leads	
Resistor of Known Value	
Spool of Copper Wire	
Pyrex Beaker	
Hot Plate	Bunsen Burner
Celcius Thermometer	

D. *Experiment 4. Electromagnetism (A Qualitative Investigation).*

As suggested by the title, this experiment leads the student through a series of demonstrations of magnetic phenomena. As a result, he will acquire qualitatively, concepts of magnetic induction, flux, and Faraday's Law. The experiment then has the student make qualitative observations on the ignition system.

LIST OF EQUIPMENT

LISTED	*ALTERNATE*
Bar Magnet	
Glass or Plaster Sheet	
Iron Filings	
Demonstration Oscilloscope	Any Beam of Charged Particles
D.C. Power Supply (at least 5 amp)	
Coil of Wire (Gilley) (2)	
Test Leads	
Magnetic Compass	
Cardboard Sheets	
Galvanometer	
Switch	
U-Shaped Iron Core for Gilley Coils	
Tap Key Switch	
Ignition Coil	
Ignition Condensor	

E. *Experiment 5. An Analysis of the Ignition System.* In this final experiment, the student analyzes the wave-form of an ignition system, and from quantitative oscilloscope data on this wave-form, he calculates values of various components of the system. This experiment requires that the student apply most of his knowledge of electromagnetics, learned so far in the module, to this system.

LIST OF EQUIPMENT

LISTED	*ALTERNATE*
12 V Lead Storage Battery	Auto Ignition System
Sun Ignition Simulator	
Test Leads	
Oscilloscope	
Ohm-Meter	Wheatstone Bridge

IV. *Answers to Problems*

Problem	*Answer*
1	2 amperes
2	1.5 volts
3	4.5×10^{-6} joules
4	12 ohms
5	2.4 amperes; 3 amperes; 4 amperes
6	0.014 ohm
7	$3.7 \times 10^{-3}/^{o}C$
8	2.4×10^{-3} newtons
9	2.9 tesla
10	1.1×10^{-3} webers
11	3 tesla
12	0.4 volts
13	3 milli henry
14	65 milli henry
15	100 volts
16	12 volts
17	2.5×10^{-3} second
18	40 micro farad
19	8.8×10^{-2} coulomb

20	2.8×10^{-2} second
21	3×10^{-4} henry
22	1.65×10^{-4} second
23	2.7×10^{3} hertz

V. *Resource Material*

A. *Transparencies*

Topic	*Module Page*	*Transparencies*
The Four-Stroke cycle, Gasoline Engine	2	Frey Scientific #F-6749
Circuit Diagram of Wheatstone Bridge	14, Exp. 2	Frey Scientific #6901
Wheatstone Bridge Measurement of Resistance	14, Exp. 2	Frey Scientific #6902
Magnetic Field	21	La Pine #Z-8662(047)
Magnetic Lines of Force	21	La Pine #Z-8662(045)
An EMF Induced by Change in Flux	33	Frey Scientific #6905
An EMF Produced only by a Change in Flux	33	Frey Scientific #6910
Oscillating L-C Circuit	59	John Wiley, #EM9

B. *Films*

Topic	*Module page and/or Experiment*	*Film*
Internal Combustion	1-8	The ABC of Internal Combustion (General Motors Film Library)
The Oscilloscope	Exp. 1	Introduction to the Cathode Ray Oscilloscope (EBEC #2604)
Electricity	10-19, Exp. 2	Principles of Electricity (G.E. Ed. Films)

C. *Film Loops*

Topic	*Module page and/or Experiment*	*Film Loops*
The Oscilloscope	Exp. 1	Some Elementary Things an Oscilloscope Can Do (EBEC #S-81502)
Ohm's Law	20, Exp. 2	Ohm's Law (International Communications Films)
Magnetism	Exp. 4	The Magnetic Field (Ealing #80-4062/1)
Electromagnetism	Exp. 4	Faraday's Law of Induction (Ealing #80-4179/1)
The R-L Circuit	59-68, Exp. 5	Series R-L Circuit (Animated Electronics Films)
The L-C Circuit	69-76	The Undamped Oscillation (Animated Electronics Films)
The L-R-C Circuit	77-78, Exp. 5	The Damped Oscillation; Series L-R-C Circuit (Animated Electronics Films)

D. *Printed References for the Teacher*

Topic	*Source*
Ignition Systems	*Ignition Systems, Principles of Operation: Training Handbook*, Course 12001 (Service Dept., Ford Division, Ford Motor Company, 1964)
Ignition System	Wall Chart--Automobile Ignition System (General Motors Educational Aids)

E. *Key for Post-Test*

1, D; 2, A; 3, E; 4, B; 5, D; 6, A; 7, E; 8, E;
9, B; 10, A; 11, C; 12, A; 13, E; 14, A; 15, B;
16, B; 17, B; 18, E; 19, D; 20, C.

Pre-Requisites
Test

THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

Prerequisites

1. When you are given a number expressed in decimal form which is greater than one, be able to write it as a number between one and ten multiplied by a positive integral power of ten (*Scientific notation*, positive exponents).

2. When you are given a number expressed in decimal form which is between zero and one, be able to write it as a number between one and ten multiplied by a negative integral power of ten (*Scientific notation*, negative exponents).

3. When you are given an indicated multiplication and division of several numbers expressed in decimal form, some between zero and one, and others greater than one, be able to write the various factors and divisors in scientific notation, and then use appropriate rules of exponents and of arithmetic to get a result which you express in scientific notation.

4. When you are given an algebraic equation involving operations of multiplication, division, addition, and subtraction (but no exponents or roots) on several numbers represented by symbols, be able to solve the equation for a specified symbol.

5. When you are given the initial and final values of a quantity, be able to use the definition of the delta prefix symbol, Δ, to find the change in the quantity. (Find ΔF, Δt, etc.)

6. When you are given a graph (which may not be a straight line) of one physical quantity as function of another, be able to find the value of the ordinate for a given value of the abscissa, and be able to calculate an approximate value of the slope for a specified value of the abscissa.

7. When you are given an equation which relates one variable to several others (which may include operations of addition, subtraction, multiplication, division, or simple roots or powers), and values of all but one variable, be able to evaluate the unknown.

Objectives

THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

Objectives

1. When you are given a glossary of *definitions* in equation form taken from those presented in the module, and values of certain electric or magnetic quantities, be able to select a correct definition and use it to calculate the value of a designated quantity. (temperature coefficient of resistance; magnetic induction; magnetic flux; etc.)
2. When you are given a set of equations, each of which summarizes a *law* or *principle* of electricity or magnetism, taken from those presented in the module, and values of certain quantities, be able to select an appropriate law and use it to calculate the value of a designated quantity (Ohm's Law; Faraday's Law; etc.).
3. When you are given the graph of some electric or magnetic quantity versus another, or versus time, and any other essential information, be able to use an appropriate property of the graph to determine the value of some designated quantity (Slope of a flux-current graph to get inductance; Slope at the origin of a current-time graph to get inductance of an L-R circuit; period of oscillation of an L-R-C circuit to get an inductance or capacitance, given one or the other of these quantities; decay time of an L-R-C circuit to get resistance; etc.).

4. When you are given several circuit diagrams which may include an inductor, capacitor, resistor, switch or battery, and the initial charge of capacitors, be able to select the circuit for which a given graph of current versus time would result when the switch is closed (L-R circuit; L-C circuit; L-R-C circuit; etc.).
5. When you are given a circuit diagram, which may be an L-R, L-C, or L-R-C circuit, the values of all components, and initial conditions, be able to calculate the appropriate value (or values) of time characteristic of that circuit (period or time constant).
6. When you are given the graph of current versus time in an ignition system, be able to infer from the graph: when the points open; how long they remain open; when the points close; how long they remain closed; when the spark plug begins to fire; how long it fires; or other information about this specific system derivable from such a graph.

Text and
Student Guide

THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

I. INTRODUCTION

The internal combustion, gasoline engine converts one kind of energy to another. Chemical energy in the gasoline is converted into heat, which then expands the combustion gases to produce mechanical energy in the form of moving parts in the engine. Eventually, this energy is transmitted to the wheels.

In order to control this energy conversion process, several conditions must be met. First, there must be a proper mixture of gasoline and air to form a combustible fuel. This mixing takes place in the carburator. There must also be a chamber in which the mixture can burn. The cylinder and movable piston provide such a chamber. There must be a means of disposing of the heat generated in the engine, so that it does not become too hot. In modern engines, a water cooling system extracts this surplus heat. Finally, there must be a means of igniting the fuel mixture. The timing of this ignition is very important to the proper operation and performance of an internal combustion engine.

The fuel can be ignited in several ways. The simplest way is to apply sufficient heat, like that provided by a lighted match. However, lighting a match is not practical when the fuel is enclosed by a container like the cylinder of a gasoline engine, and when the process must be repeated frequently, as it must in such engines. As a matter of fact, the earliest ignition system (1838) for an internal combustion engine did use a flame for ignition. In a chamber adjacent to the cylinder, there was a pilot flame. Because the pilot flame was extinguished after each combustion, it had to be relighted before the next ignition. This system was therefore modified to include a hot tube which was kept hot by a pilot flame located outside the cylinder. The disadvantage of these methods was that the fuel was not always ignited at the optimum time. This difficulty led to the introduction of the electric spark ignition, the timing of which was easily controlled.

The first electric spark ignition system employed a switch which was opened by the piston as it reached the top of its travel in the cylinder. The opening of this switch by the piston interrupted an electric current through a coil of wire, so that a spark was produced across the switch. The position of the switch inside the cylinder resulted in difficult servicing problems, since the engine had to be disassembled to get to the switch.

The first high-voltage electric spark system employed a spark plug and a magneto. Most of you already know what a spark plug is. A magneto is basically a magnet which moves rapidly past a coil of wire, producing a high voltage.

For various reasons, the magneto was replaced in most internal combustion engines by the battery powered ignition system which will be examined in this module. A still newer ignition system, employing modern, solid state electronic components, is becoming common; however, such systems will not be considered here.

The purpose of the ignition system of an automobile is to ignite the gasoline-air mixture in the cylinders of the engine at the correct time. The word, system, is used in technology to mean a group of components which work together to serve a common purpose. Figure 1 shows the components of a typical ignition system. The battery, ballast resistor, coil, distributor and spark plug are the five components which function together to provide ignition in the engine cylinders.

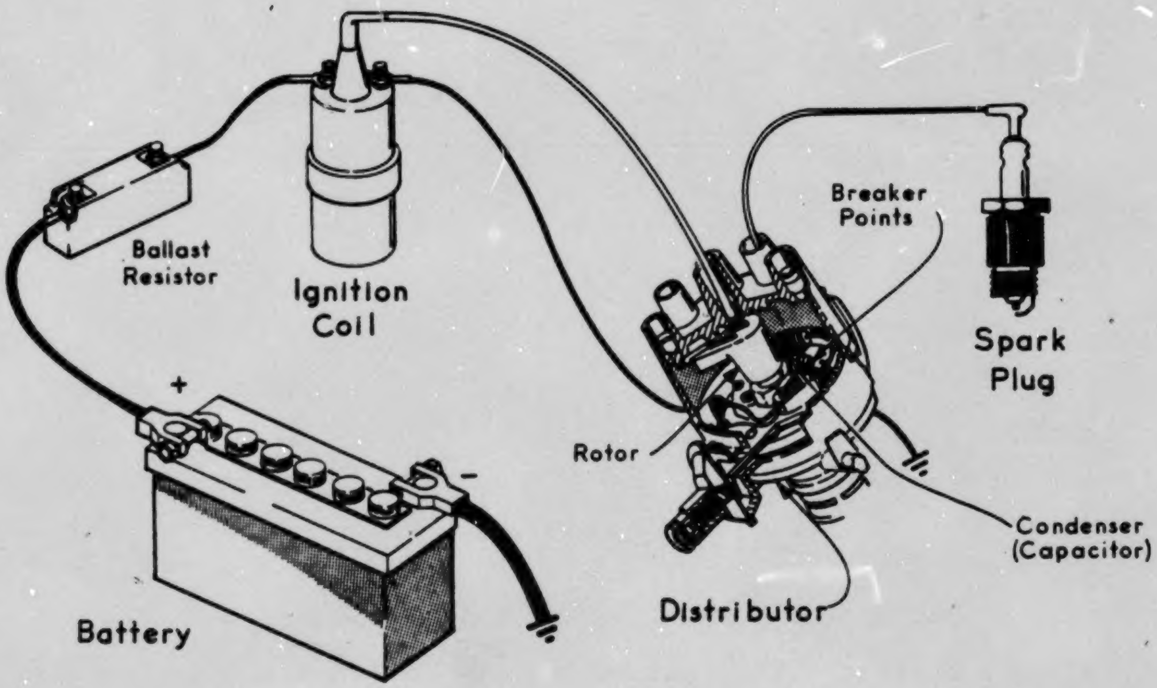
Breaker Points
Ballast Resistor
Ignition Coil
Spark Plug
+
Rotor
-
Condenser (Capacitor)
Distributor
Battery

Figure 1

Automotive engines are of a variety known as four stroke (or less accurately as four cycle) engines. They might have four, six or eight cylinders like the one shown in Figure 2.

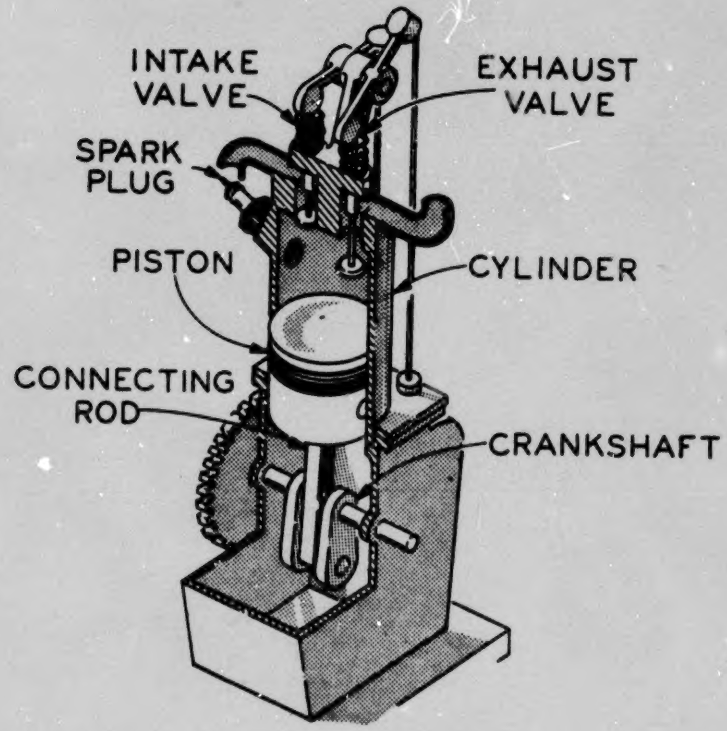
INTAKE VALVE
EXHAUST VALVE
SPARK PLUG
PISTON
CYLINDER
CONNECTING ROD
CRANKSHAFT

Figure 2

Each cylinder contains a "piston" connected by means of a "connecting rod" to a crank shaft shared in common with the other cylinders. The cylinders might be arranged in a line, VEE, or an opposed piston configuration.

Although cylinders are arranged with respect to the crank shaft of an engine so that no two cylinders have the same thing going on at the same time, the function of each cylinder is the same. The first of the four strokes is called the intake stroke. As the crank of a given cylinder moves past its top dead center position, the intake valve opens. The piston travels downward, as shown in Figure 3a, drawing in a mixture of gasoline vapor and air from the carburator. The intake valve remains open until the piston has traveled almost completely downward and the cylinder is filled with a mixture of vaporous fuel and air. At the lowest point of piston travel the intake valve has closed, and the piston begins the second of the four strokes called the compression stroke.

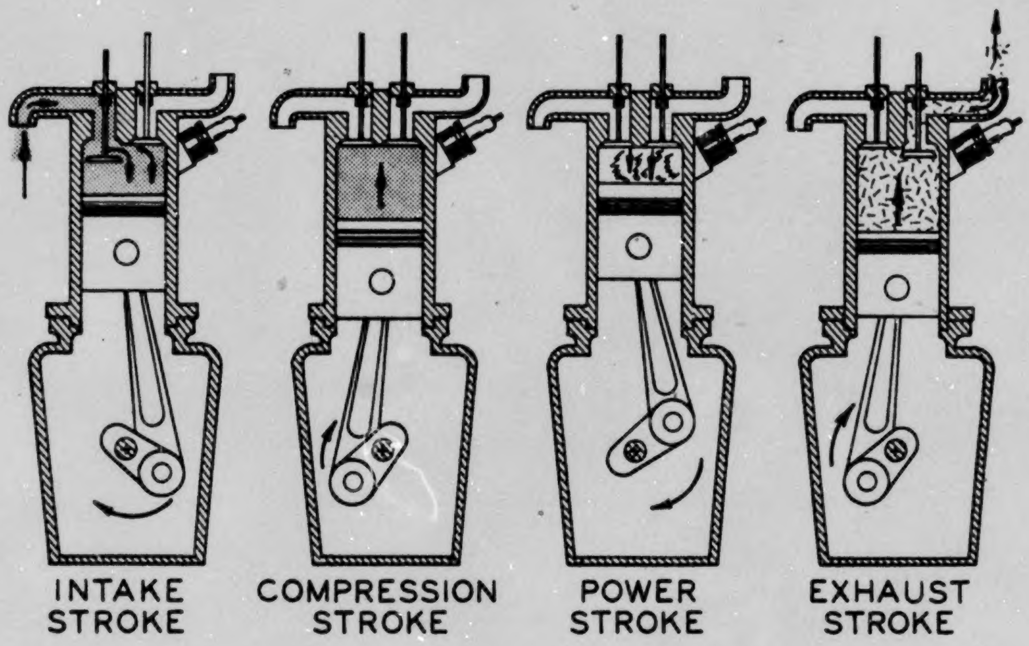

Figure 3
The four stroke engine.

With both valves closed as shown in Figure 3b, the fuel-air mixture is unable to escape. As the piston returns to its uppermost position, it compresses the mix to about 1/8 its original volume. By compressing the mixture before ignition, the efficiency of the engine is improved.

As the piston comes once again to top dead center, the valves remain closed, and the compressed fuel-air mixture is ignited by the spark plug. The piston then begins the power stroke, as shown in Figure 3c. The high pressures caused by the heat of combustion force the piston downward. This causes the crank to turn. The amount of work delivered during the power stroke far exceeds the combined total work required for the other three strokes.

The final stroke of the four stroke engine is the exhaust stroke. As the crank passes bottom dead center upon completion of the power stroke, the exhaust valve is opened. When the piston travels up on this last stroke, as shown in Figure 3d, it forces the products of combustion out the exhaust pipe.

At top dead center of the power stroke, the piston is in the optimum position to begin receiving the energy of combustion and transferring it to the engine shaft. The spark normally should not occur at the beginning of the power stroke. Because it takes time for the flame front to pass from the spark plug through the combustible mixture, it is most efficient to produce the spark in advance of the top dead center position. This is called "*spark advance*". In this way, most combustion is completed early in the power stroke. But the optimum amount of spark advance depends upon the speed of the engine. It also depends upon the amount which the accelerator has been depressed. Spark advance mechanisms are built into the distributor. In order to improve pollution control, several other factors must influence spark advance. At the time of this writing, cars are being produced which vary spark advance with engine speed, accelerator depression, air temperature and vehicle speed.

It is the distributor which conducts the spark to the proper spark plug of an engine at the proper time. The distributor is mounted directly on the engine, and the rotating shaft of the distributor is turned at a speed one half that of the engine speed. In this way a spark occurs only on the compression stroke, rather than also on the exhaust stroke. The rotor arm at the top of the shaft points, in turn, to each of the spark plug wire contacts in the distributor cap. The spark plugs must be wired to the distributor cap in the proper sequence according to the firing order of the engine cylinders. For six cylinder engines the firing order is 1-5-3-6-2-4, where the cylinders of the engine are numbered from front to rear. The firing orders of eight cylinder engines vary from engine to engine.

Getting the spark to the right cylinder at the right time is just one part of the ignition system function. The system must also produce the sparks. A high voltage (4000 to 20,000V) is needed to make an electric spark jump even the fraction of an inch in a spark plug gap. Yet only 6 or 12 volts are available from the battery. It is, therefore, a function of the ignition system to increase the voltage by the necessary amount. This increase in voltage by a factor of about 1000 may seem like an impossible requirement; however, the high voltage is required only in spurts of less than thousandth of a second in duration. Meanwhile the battery voltage is continuously available. The ignition system can draw electric energy at low voltage from the battery for a relatively long period of time. Then it can deliver this energy to a spark plug at a high voltage for a very brief period of time. If the high voltage were required for long periods of time, the ignition system as we know it could not do the job.

The ignition system performs its voltage increase in the following way. As shown in Figure 4 a pair of "breaker points" and a cam are housed within the distributor. The cam turns with the distributor rotor at half the engine speed. One of the breaker points is on a spring-loaded arm which rides on the cam. The cam has as many high points as the engine has cylinders; therefore, as the rotor turns, the points open and close once for each cylinder in the engine.

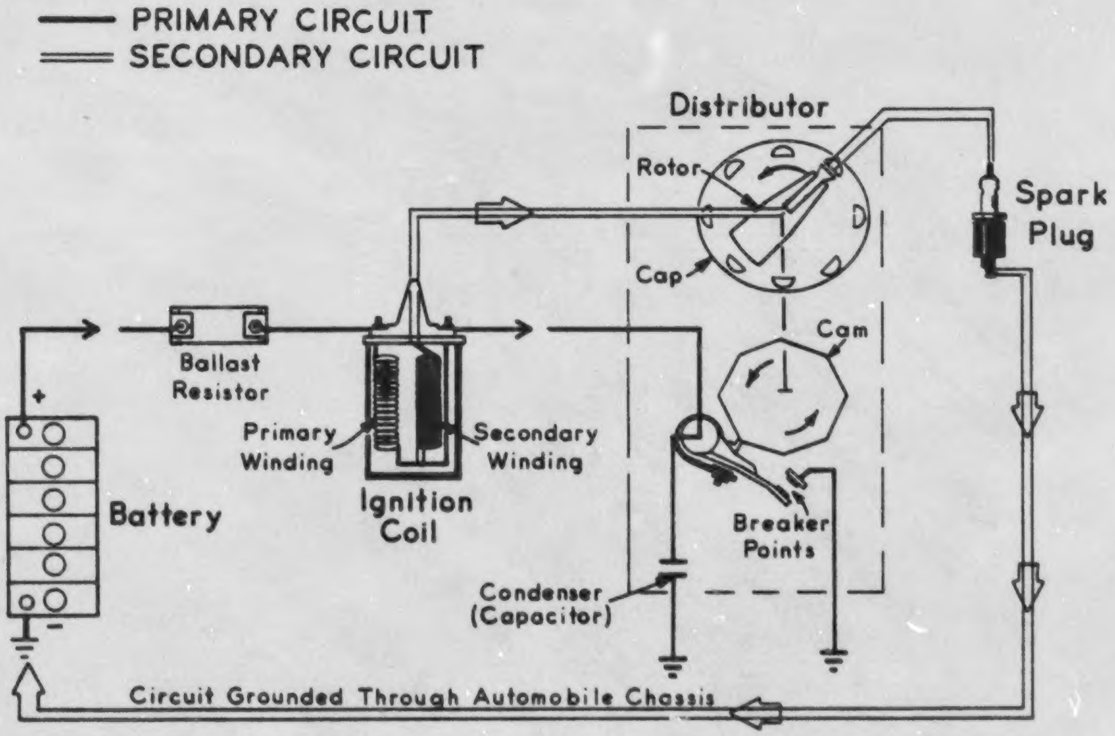
PRIMARY CIRCUIT
SECONDARY CIRCUIT
Distributor
Rotor
Cap
Spark Plug
Cam
Ballast Resistor
+
Primary Winding
Secondary Winding
Battery
Ignition Coil
Breaker Points
Condenser (Capacitor)
-
Circuit Grounded Through Automobile Chassis

Figure 4

When the points are closed, there is an electric current in the "primary" or low voltage circuit of the system shown in the pictorial diagram of Figure 4. The electric current passes from the battery through the ballast resistor, primary windings of the ignition coil, the closed breaker points and back to the battery through the automobile chassis. When the breaker points are opened by the distributor cam, the electric current in the primary circuit is interrupted. By interrupting the current in the primary windings of the ignition coil, thousands of volts are produced in the "secondary" or high voltage coil. This high voltage produces an electric current through the rotor, the cap, to the spark plug and across its gap.

The ignition coil will be discussed in more detail later. The essential things to know at this point are that it contains two coils of wire, and that a sudden interruption of electric current in the primary coil produces thousands of volts in the secondary coil. This interesting phenomenon is called "electromagnetic induction". At this point you should familiarize yourself with the ignition system by completing *Experiment 1, An Examination of the Ignition System.*

EXPERIMENT I

AN EXAMINATION OF THE IGNITION SYSTEM

The purpose of this experiment is to familiarize you with the principal components of the ignition system of an automobile. First you should examine the system and identify the following components:

A. *Battery (12 v).* Note that the red lead is connected to the positive terminal of the battery.

B. *Ignition Switch.* The ignition switch is simply an "ON" and "OFF" switch which connects the battery to the circuit.

C. *Ballast Resistor.* The ballast resistor is encased in a white block of ceramic material for electric and thermal insulation. It is located in the circuit between the battery and the positive terminal of the ignition coil.

D. *Ignition Coil.* The ignition coil is in an iron case. The coil has three terminals. The central terminal is one lead of the secondary (high voltage) winding of the ignition coil. It is connected to the central terminal of the distributor. The terminal marked "+" is connected through the ballast resistor to the positive terminal of the battery. The remaining terminal, marked "-", is connected to the breaker arm in the distributor. These two terminals make up the primary of the ignition coil.

E. *Distributor.* The distributor is made up of several sub-assemblies:

1. *Distributor Cap*: This cap is highly insulated and made of bakelite; it fits snugly over the distributor housing, and it is retained by two clips. The cap contains the spark plug cable towers arranged evenly around the outer edge, as well as a cable tower located in the center of the cap to receive the high voltage current from the ignition coil.
2. The *rotor* fits over the cam and rotates with the shaft.
3. The *breaker arm* is an assembly which rubs against an eight-lobed cam which opens and closes the *breaker points*. One of the points is stationary and the other is on the breaker-arm assembly. Opening and closing of these points interrupts the current in the primary circuit.
4. *Capacitor.* The capacitor is contained in a metal cylinder. The cylinder is grounded to the system and forms one terminal of the capacitor. A black wire connects the other side of the capacitor to the breaker arm and points.

F. *Spark Plug.*

Remark: The following observations require the use of a cathode ray oscilloscope. Instructions for use of this instrument are given in the appendix to this experiment. Acquaint yourself with the oscilloscope by performing the exercises outlined in the appendix.

WAVEFORM ACROSS THE BALLAST RESISTOR

Connect the lead wires of the vertical input of the oscilloscope across the terminals of the ceramic ballast resistor. Turn on the motor to rotate the cam, and turn on the ignition switch It may be necessary to reverse the leads on the ballast resistor to obtain the desired waveform. (Note: Make certain that the ignition switch is turned off before handling the lead wires. High voltages are produced in the ignition coil when the ignition switch is on.)

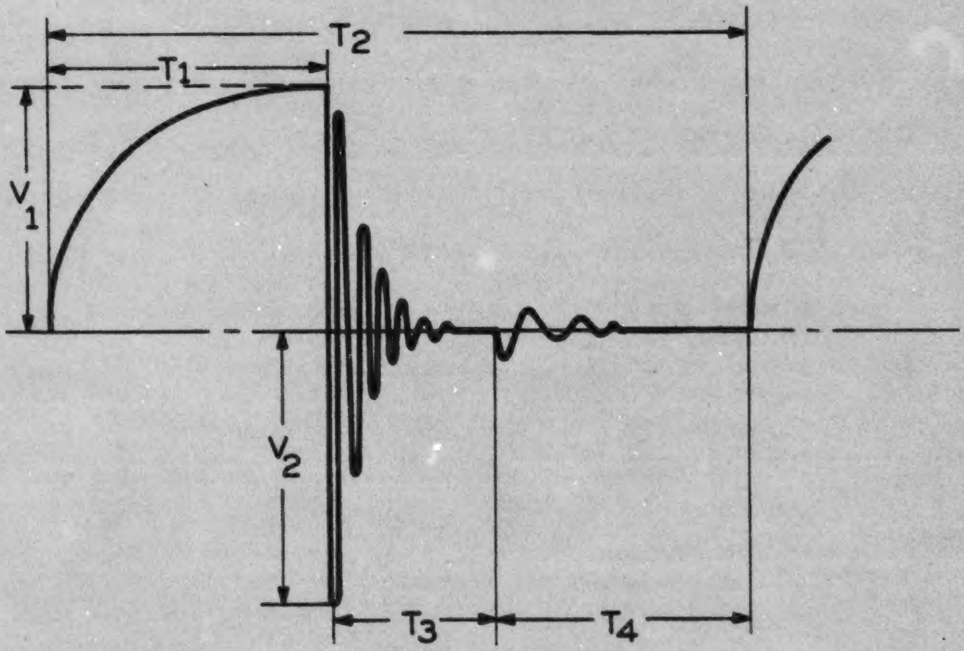

Figure 1

Obtain a waveform pattern similar to the one shown in Figure 1. You will need to adjust the time base (horizontal display), the volts/cm vertical display, the stability control, and the trigger level.

Study the wave form and draw a sketch of it. Measure and record the following quantities.

a. The maximum voltage, V_1, during build up of the current.

b. The maximum current $I = V_1/R_B$. The value of the ballast resistor, R_B, is 1.95 ohms.

c. The time T_1 for current build up.

d. The time interval T_2 between firings of the spark plug.

Turn the ignition switch off.

WAVEFORM ACROSS PRIMARY WINDING OF THE IGNITION COIL

Connect the vertical input of the oscilloscope to the two primary terminals (see Figure 4 in Student Guide) of the ignition coil. Make suitable adjustments of the oscilloscope controls and obtain a wave pattern of the form shown in Figure 2. Use the same rotor speed used in the previous exercise. The leads may need to be reversed in order to obtain the pattern of Figure 2. (Remember to turn off the ignition switch before handling the lead-wires.)

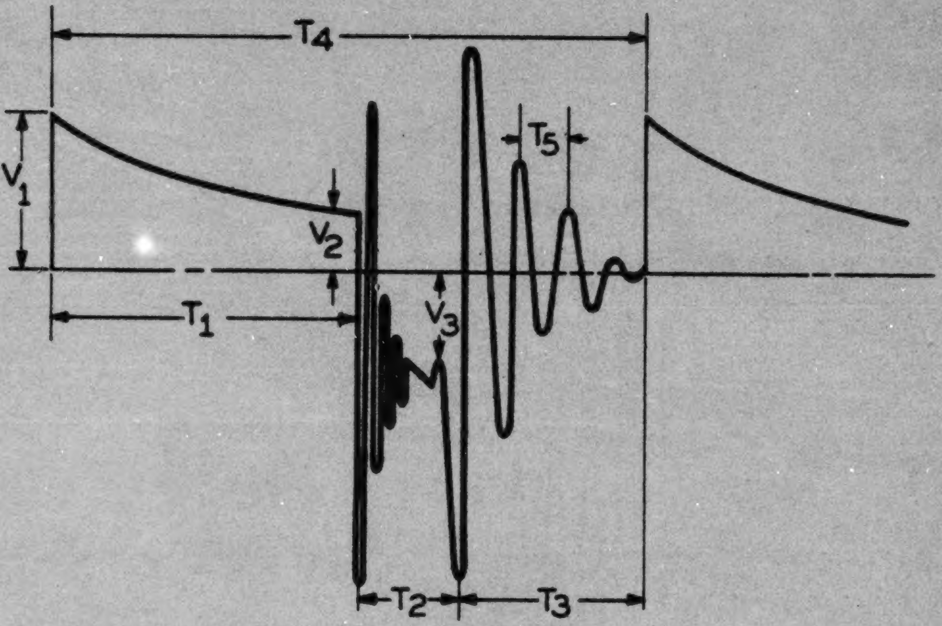

Figure 2

Using appropriate settings of the time base, you should now measure and record the following quantities: (The time intervals in Figure 2 do not correspond to the times indicated in Figure 1.)

a. The voltage V_1.

b. The voltage V_2.

c. The time interval T_1.

d. The time interval T_2.

e. The time interval T_3.

f. The time interval T_4.

Obtain approximate values for:

g. The period of oscillation T_5.

h. The voltage V_3.

Change the sweep time on the oscilloscope and expand the high frequency oscillation to obtain a pattern of the form shown in Figure 3.

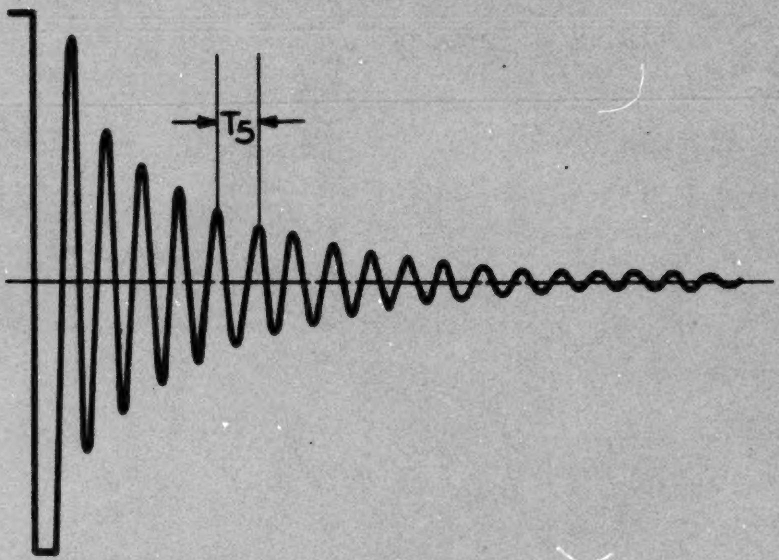

Figure 3

Determine the period of oscillation T_5.

Make a complete record of your observations, and keep them for future reference.

APPENDIX (THE CATHODE-RAY OSCILLOSCOPE)

The cathode-ray oscilloscope is a useful and versatile instrument. In proper use, nearly any kind of electric signal can be presented visually. The oscilloscope provides the technician with a method of seeing what happens in the electronic circuits with which he works. By means of suitable transducers (devices that convert one form of energy into electric energy) mechanical vibrations, pressure changes, temperature changes, sound level changes, etc. may be changed into electric signals. Some examples of transducers are strain gauges, resistance thermometers, piezoelectric crystals, microphones and photocells.

The oscilloscope gives a visual display of the amplitude, frequency and waveform for an input signal. The purpose of this discussion is to provide instruction on the use of the oscilloscope. We need not concern ourselves with its inner workings, but only with the functions of the external controls. This discussion will be restricted to the basic, general-purpose oscilloscope. Some oscilloscopes have a number of features which are added to increase their usefulness. The reader should refer to the operating instructions for the specific oscilloscope he intends to use.

The basic functions included in a general-purpose oscilloscope are listed below:

1. *Intensity* control to vary the brightness of the beam.
2. *Focus* control to give a clear, sharp trace on the screen.
3. *Vertical positioning control* to vary the vertical position of the trace.

4. *Horizontal positioning control* to vary the horizontal position of the trace.
5. *Horizontal Time base sweep* to vary the rate at which the trace sweeps across the screen.
6. *Synchronization* or *Trigger* controls to stabilize the repetitive wave pattern so that it will "stand still".
7. *Vertical* and *horizontal* amplifiers and controls to adjust the amplitude of a signal.

The following exercise is given to acquaint you with the Heathkit Model 10-14 oscilloscope. Refer to Figure 4.

Operating Procedure for Heathkit Model 10-14.

1. Set TRIGGER SOURCE (14) switch to INT. and the TRIGGER MODE switches to (+) (16), AC (18) and NORM (17).
2. TURN TRIGGER LEVEL (20) control fully clockwise. Turn the STABILITY (19) control fully clockwise.
3. Set HOR. DISPLAY (25) switch to X1 position; the MULTIPLIER (22) to 2; the TIME/CM to 1 m SEC.
4. Set VOLT/CM (11) switch to 10 volts/cm. GAIN (7) TO CAL position.
5. Turn SCALE ILLUM. (1) control clockwise to turn scope on. Adjust INTENSITY (4), FOCUS (3), and ASTIG. (2) controls to obtain a sharp clear display.
6. Adjust the VERTICAL POSITIONING (12) to center the trace vertically. Adjust HORIZONTAL POSITION (13) so that the left edge of the trace is just inside the left edge of the graduated scale.

7. Connect a square wave oscillator to the VERTICAL INPUT (6). Set the frequency of the oscillator to 1000 c/s. Turn the oscillator on. Adjust the output level of the oscillator, or adjust the VOLT/CM (11) switch on the scope, to obtain about a 4 cm vertical deflection.
8. Turn the STABILITY (19) counter clockwise until the trace just disappears. The stability control should remain in this position, as it will seldom need adjustment.
9. Turn TRIGGER LEVEL (20) control to about the center of its rotation where a stable "standstill" trace should appear. There is no fixed rule for setting the trigger level control. It is set to obtain a "standstill" pattern for each type of waveform.
10. Adjust the VERTICAL (12) and HORIZONTAL POSITIONING (13) controls to center the trace.

Change the Trigger Mode switch from (+) to (-). The trace should flip over, so that the trace begins on the negative portion of the cycle. A slight adjustment of the Trigger Level may be necessary to achieve this result.

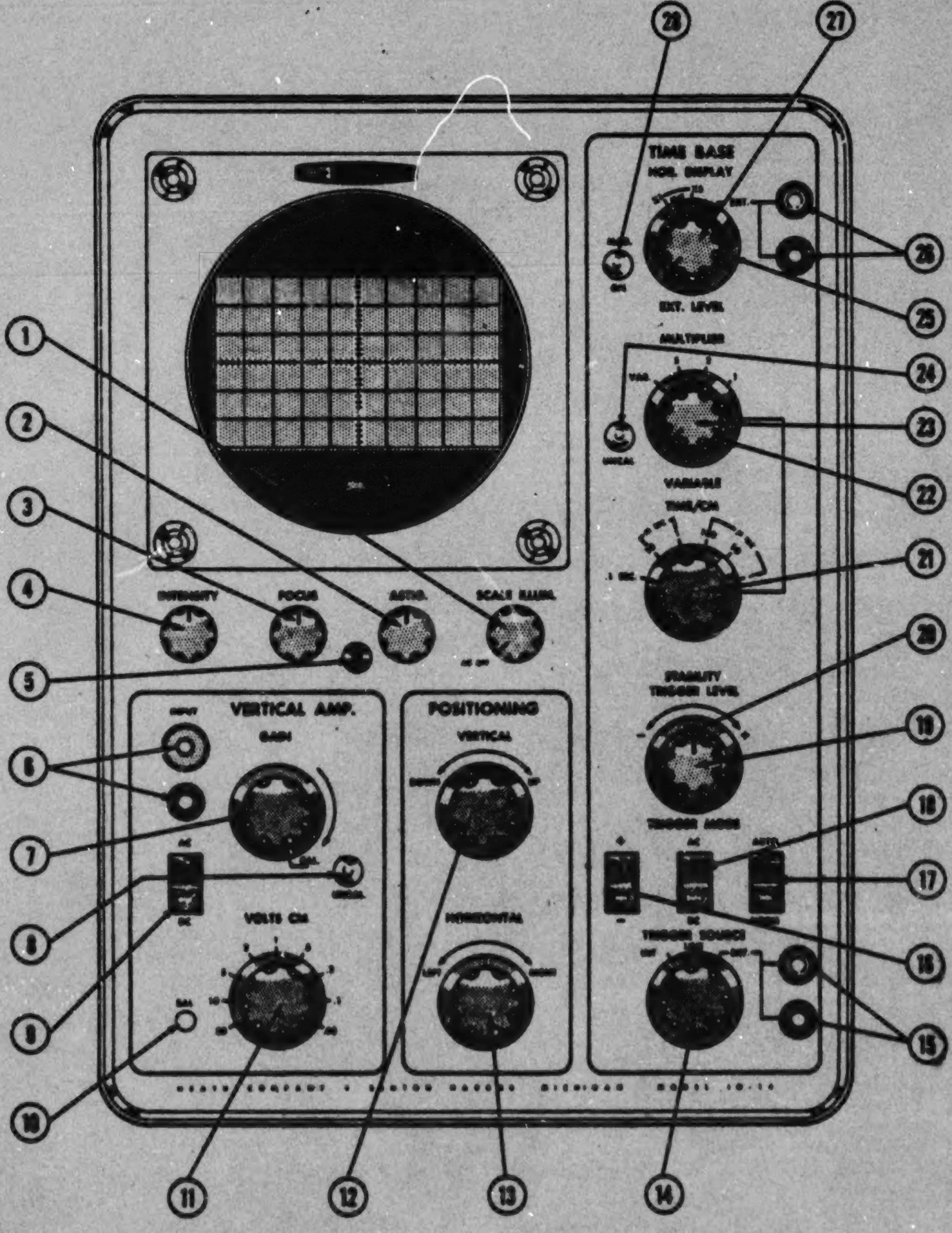
TIME BASE
HOR. DISPLAY
EXT.
EXT. LEVEL
MULTIPLIER
UNCAL
VARIABLE
TIME/CM
STABILITY
TRIGGER LEVEL
TRIGGER MODE
AC
DC
AUTO
TRIGGER SOURCE
INTENSITY
FOCUS
ASTIG.
SCALE ILLUM.
VERTICAL AMP.
INPUT
GAIN
AC
DC
UNCAL
VOLTS CM
BAL
POSITIONING
VERTICAL
HORIZONTAL
LEFT
RIGHT
1
2
3
4
5
6
7
8
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Figure 4

Adjust the Time Base controls to obtain 4 cycles displayed on the oscilloscope. To obtain this sweep time we must make use of each of the time base controls. The HORIZONTAL DISPLAY switch is set to X5, the MULTIPLIER to 2 and the TIME/CM to 1 m-SEC. The X5 setting divides the Multiplier and Time/cm setting by 5. This means that the rate of sweep across the scope is 4 times the period of the source. If the frequency of the signal is 1000 c/s the period, or time to complete one cycle, is the inverse of the frequency; for our case, T = 1/1000 c/s or one millisec. When four cycles appear on the scope, the time required to sweep the 10 cm across the scope is 4×10^{-3} s/10 cm = 4×10^{-4} s/cm. The time interval per cm of sweep for the above settings is $(2 \times 10^{-3}\ \text{s})5 = 4 \times 10^{-4}$ s. This is the desired sweep time.

Obtain a pattern with 10 cycles. Record the time base settings. Obtain a pattern having a single cycle. Record the time base setting. Determine the voltage of the waveform from the vertical amplifier settings. Set the frequency of the oscillator to some arbitrary value and obtain a stable trace on the scope. Determine the period of oscillation by determining the distance along the horizontal axis that is required for 10 complete cycles of oscillation. For this case 10T = (Time/cm) x (number of cm.) The frequency of oscillation is $f = \frac{1}{T}$. The above exercise should provide enough background for you to proceed with the experiments in this module.

II. ELECTRIC CURRENT

The magnetic properties of electric currents underly the operation of an automotive ignition system. Electric current is the flow of electric charge. It has been known for about two centuries that there are two types of electric charge, designated positive and negative for convenience. It is also known that between any two charges, electric forces act, and that unlike charges attract and like charges repel. Everyone is familiar with static electricity. For example, when a comb is run through dry hair, the hair will be attracted to the comb because the hair has picked up a positive charge while the comb has acquired a negative charge. The strands of hair will tend to stand up and away from each other because they have the same charge. The unit of charge is called the coulomb, after the scientist who discovered the law of these electric forces. The unit "coulomb" is conventionally represented by the letter "C".

Most matter is electrically neutral because it contains equal amounts of positive and negative charge. Even the individual atoms, the basic building blocks of matter, ordinarily contain equal amounts of positive and negative charge. In an atom, the positive charge is in a small region called the nucleus, where most of the atomic mass is concentrated. The negative charge of an atom is contained in lighter particles, called electrons, which swarm around the nucleus. It is the electrons that usually move as electric current. For example, in the case of combing dry hair, electrons are transferred from the hair to the comb, leaving behind some atoms with a net positive charge. In the ignition system circuits, it is electrons which move through the wires, but inside the battery, current is composed of positively and negatively charged atoms moving in opposite directions.

The concept of electric current may be made quantitative by considering the net amount of charge per unit time that passes through an area.* If a charge Q moves through an area in a time t, then the current I is defined as

$$\boxed{I = Q/t.} \quad \text{(Definition of electric current)} \qquad (1)$$

The units for current are called amperes (one ampere = one coulomb per second). The letter "A" is conventionally used to represent the word, "ampere".

Example Problem

What is the current in a wire where 120 coulombs of charge flow through a cross-section of the wire in a time of 1 minute?

Solution

Given are

$$Q = 120 \text{ coulomb and } t = 1 \text{ minute.}$$

In order to use the equation, I = Q/t, the time must be expressed in seconds. Taking the time as 60 seconds we have

$$I = \frac{120 \text{ coulombs}}{60 \text{ seconds}} .$$

---

*When referring to an electric circuit diagram, where wires are considered to be lines, we can define current as the net charge passing a point per unit of time.

Dividing, as indicated,

$$I = 2 \text{ coulomb/second.}$$

Since 1 coulomb/second = 1 ampere, the solution becomes

$$I = 2 \text{ amperes.}$$

Problem 1

If 3600 coulombs of charge flow through a cross-section of wire in 30 minutes, what is the current in the wire?

Question 1

The flow of a fluid can be described using a current defined as the mass of fluid per second passing through an area. How is such a current analogous with an electric current?

Charge carriers (electrons in metals and positive and negative ions in solutions) may move when acted upon by an electric force. Such a force is due to the presence of other charges. When a charged particle moves under the action of a force, there may be something called *work* done on or by the particle.

We define *work* as the force acting on an object times the distance through which the object moves, where the force is a push or pull in the direction of motion. When one object does work on another, something we call *energy* is transferred from the first object to the second. If you push on an object through some distance, and the only result of your pushing is to speed it up, the work you are doing on the object appears as *kinetic energy*, a term we use to refer to the energy of motion. If you push on an object through some distance, and its speed is the same when you finished pushing as when you started, the energy you transferred to it must have gone somewhere. Suppose the object were a box on the floor, and you pushed it to the other side of the room. Let us assume that the box was at rest when you started pushing and when you stopped; yet you did work on the box. In this case, if you felt the bottom of the box, you would find that it was warm. The floor was also warmed slightly. The work you did on the box was equal to the work done between the box and the floor. The energy you transferred to the box was transferred right back out again in the form of heat. What if you push on an object through a distance, but it neither speeds up nor gets warm? You have done work on the object, and the resulting energy transferred does not just disappear. In such a case, the object changed its position, and the energy was stored as *potential energy*. For example, if you lifted the box to a certain height, the work you did on the box has been stored as gravitational, potential energy. You can get the energy back again by letting the box fall from that height. When you do, the box will speed up as it falls, converting potential energy to kinetic energy, until, just as it hits the floor, it has a kinetic energy equal to the work you originally did when you lifted it.

Coulomb demonstrated that the electric force which a charged particle has exerted on it is proportional to the magnitude of its charge. The amount of work done on a charged particle, as it moves in space, is also proportional to the magnitude of its charge. There is a useful quantity which is related to the work done on the charged particle, but which does not depend upon the magnitude of its charge. This quantity is obtained by dividing the work done on the particle to increase its potential energy by the magnitude of its charge. We call this quantity the work per unit charge, or the potential difference. If Q represents the amount of charge moved, and W represents the work done in moving it, the potential difference V between two points in space is defined by the equation

$$V = W/Q. \quad \text{(Definition of voltage)} \qquad (2)$$

This work per unit charge, also called voltage, is now independent of the charge Q and depends only on the two points in space. Work, W, is expressed in units called joules, represented by the letter, "J", charge, Q, is in coulombs, and the potential difference, V, is then in volts.

Example Problem

What is the potential difference between two points, if 6 joules of work are done in moving 2 coulombs of charge between the points?

Solution

Given are

$$W = 6 \text{ joules and } Q = 2 \text{ coulombs.}$$

Substituting these values into the equation, $V = \frac{W}{Q}$,

$$V = \frac{6 \text{ joules}}{2 \text{ coulombs}}.$$

Performing the indicated division yields

$$V = 3 \text{ joules/coulomb.}$$

Since the unit of potential difference has been defined as

$$1 \text{ volt} = 1 \text{ joule/coulomb,}$$

our solution becomes

$$V = 3 \text{ volts}.$$

Problem 2

What is the potential difference between two points, if 3.6 joules of work are done as a particle having 2.4 coulombs of charge moves between these points?

Example Problem

How much work is done on a particle having 5×10^{-3} coulombs of charge when the particle moves through a potential difference of 2 volts?

Solution

Given are

$$Q = 5 \times 10^{-3} \text{ coulombs and } V = 2 \text{ volts}.$$

First, the equation, $V = W/Q$, must be solved for W. This may be accomplished by multiplying both sides of the equation by Q, giving

$$VQ = W.$$

Substituting given values into this equation,

$$W = (2 \text{ volts}) \times (5 \times 10^{-3} \text{ coulombs}).$$

Performing the indicated multiplication and grouping the units together gives

$$W = 10 \times 10^{-3} \text{ volt} \times \text{coulomb},$$

which can be simplified to

$$W = 10^{-2} \text{ volt x coulomb.}$$

The unit of work was defined earlier to be the joule. Since 1 volt = 1 joule/coulomb, we obtain

$$W = 10^{-2} \left(\frac{\text{joule}}{\text{coulomb}}\right) \text{ x (coulomb),}$$

which simplifies to

$$W = 10^{-2} \text{ joules.}$$

Problem 3

How much work is done on a particle having 3 x 10^{-6} coulombs of charge when it moves through a potential difference of 1.5 volts?

The fact that nature has chosen to make the world out of two types of charge produces other complications when we consider the transport of charge from one point to another. This process is described in terms of current, which we have defined as the amount of charge which passes through a reference surface per unit of time. Negative charge produces negative currents, and the total current is the difference between the positive current and the negative current. For example, three positive charges moving through a surface in a certain time produce the same current as 4 positive charges and one negative charge or 20 positive charges and 17 negative charges. A positive charge moving from left to right produces the same charge transport as a negative charge moving from right to left.

Question 2

In a solution of copper sulfate, positive charges can be made to move in one direction, while an equal number of negative charges move in the opposite direction. Under these conditions, is there an electric current?

A *circuit* is a set of electrical components wired together to offer a closed path for an electric current. As shown in the circuit of Figure 1 of Experiment 2, there may also be several branch paths. That figure is an example of a *circuit diagram*. In a circuit diagram, the various circuit elements are connected by *leads*. The voltage source, voltmeter, resistor, milliameter and rheostat are, in this case, the circuit elements. There is, or may be, a potential difference across each circuit element and a current through each element. The relationship between the potential difference across each circuit element and the current in it is a characteristic of the element.

Because current must flow through a circuit element, each must have at least two leads, one for current to flow into the circuit element, and the other for current to flow out. The leads are shown as lines between circuit elements. We assume that leads have certain properties: There is no potential difference between two points on the same lead. The current in a lead is the same for all points along that lead. It doesn't matter how long a lead is or into what shape it is bent. It matters only what point is connected by a lead to another point.

A conductor is a material which contains free charge carriers. If such a material is placed in an electric field, the carriers will distribute themselves so that every point in the conductor is at the same potential (it becomes an *equipotential*). Thus it is impossible to maintain a current in a conductor with an electrostatic field arising outside the conductor (although when the charges redistribute themselves, there is a current, this happens at essentially the speed of light and then stops).

We know that there are currents in conductors, therefore, something must force one end of a conductor to remain at a higher potential than the other end. This something is called an electromotive force (EMF), and it may manifest itself as a battery or as a time varying magnetic field.

Another way of looking at this situation is as follows: If there is a potential difference between the ends of a conductor (say a piece of wire), charge will start to move in the wire. The charges that move through a potential difference would bring the voltage down to zero if there were not some way of transporting the charges back to the high potential region. This task is the job of the battery in a circuit like that of the primary of an ignition system. Thus, the charges continue traveling around the closed path of the circuit as long as the battery can maintain the voltage by converting stored chemical energy into electric energy.

Question 3

Give three specific examples of sources of EMF.

You should now discover a quantitative relationship between current and voltage by doing *Experiment 2, Relationship of Current to Voltage in a Conductor*.

EXPERIMENT 2

THE RELATIONSHIP OF VOLTAGE TO CURRENT FOR A CONDUCTOR

Voltage (potential difference) and current are two concepts basic to the study of electricity. The voltage is the amount of work necessary to move a unit charge between two points in a circuit, and the current is the amount of charge that flows across a surface between these points per second. The voltage is measured in units of volts; the current in amperes. Is there a relationship between the voltage and current? It is the purpose of this experiment to find such a relationship, if it exists.

The circuit to be used is diagrammed in Figure 1.

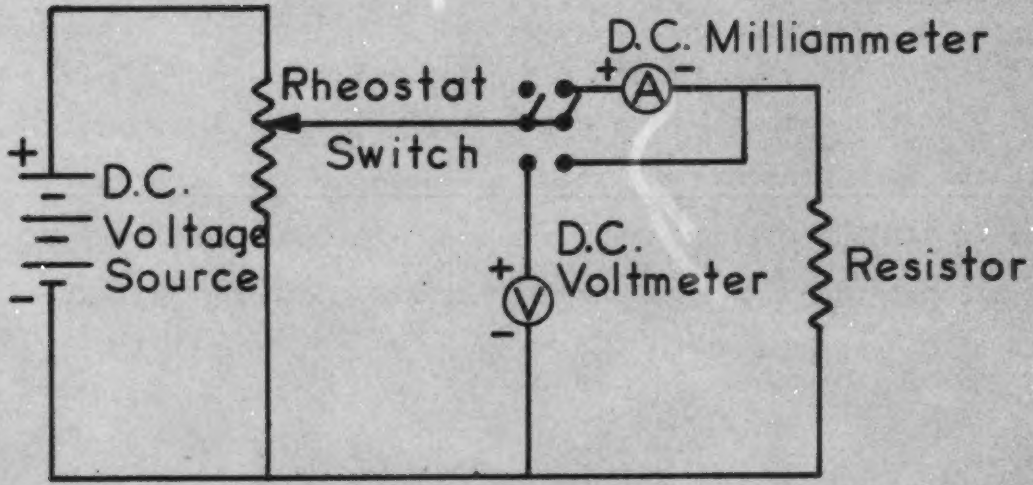

D.C. Milliammeter
+
A
-
Rheostat
Switch
+
D.C.
Voltage
Source
-
D.C.
Voltmeter
+
V
-
Resistor

Figure 1

The rheostat allows the adjustment of the voltage, and it may be just the control on the power supply you are using. The current through the resistor is read on the milliammeter. The milliammeter readings are to be recorded in units of amperes. This can be done by multiplying the milliammeter readings by 10^{-3}. For example a reading of 57 ma is $57 \times 10^{-3} = .057$ ampere. The direct current voltmeter reads the voltage across the spool of wire which serves as a resistor.

Procedure

Set up the circuit diagrammed in Figure 1. Vary the voltage, and for at least five different values of voltage (V), read the current (I). Switch S is a double-pole, double-throw switch which allows you to switch either the milliammeter or the voltmeter into the circuit, one at a time. In this way the effect of one meter cannot introduce errors into the reading of the other. Record your data for at least three different resistors and plot a graph of V on the vertical axis and I on the horizontal axis for each resistor. Determine the slope of these graphs. How is V related to I? If the relationship is a proportion, what is the proportionality constant for each case? What are the units for each proportionality constant?

In Experiment 2 you found that current is proportional to voltage in a conductor. This relationship is usually expressed with the constant of proportionality multiplied times the current,

$$\boxed{V = IR.} \quad \text{(Ohm's law)} \qquad (3)$$

The constant of proportionality, R, is called electric resistance. Equation (3) is known as Ohm's law and units of resistance are called ohms (1 ohm = 1 volt/ampere). The symbol for the ohm is the Greek letter "Ω". Since $I = V/R$, the larger the resistance of the conductor, the less the current for any given potential difference.

Example Problem

What is the resistance in the 12 volt primary circuit of an automobile ignition system where there is a current of 2 amperes?

Solution

Given in the problem are

$$V = 12 \text{ volts and } I = 2 \text{ amperes.}$$

In order to use Ohm's law, it must first be solved for the resistance, R. Dividing both sides of the equation, $V = IR$, by I, we have

$$\frac{V}{I} = R.$$

Now, substituting known quantities into this equation,

$$R = \frac{12\text{ volts}}{2\text{ amperes}}, \text{ or}$$

$$R = 6\text{ volts/ampere.}$$

The unit of resistance defined earlier was, 1 ohm = 1 volt/ampere; therefore,

$$R = 6\text{ ohms.}$$

Problem 4

What is the resistance of a conductor in which 1/2 ampere of current flows when 6 volts is applied across its ends?

Example Problem

Find the current in a wire with a resistance of 10 ohms and a potential difference of 6 volts across it.

Solution

Given in the problem are

$$R = 10\text{ ohms and } V = 6\text{ volts.}$$

When Ohm's law is solved for current, it becomes

$$I = \frac{V}{R}.$$

Substituting values for V and R,

$$I = \frac{6\text{ volts}}{10\text{ ohms}} \text{ or}$$

$$I = 0.6\text{ volts/ohm.}$$

Using the definition of the ohm,

$$I = 0.6\,\frac{(\text{volts})}{(\text{volts/ampere})},$$

which simplifies to

$$I = 0.6 \text{ ampere, or}$$

$$I = 0.6 \text{ A.}$$

From this point on, the word ampere will be represented by the letter "A".

Problem 5

Find the current in a wire with a resistance of 5 ohms and a potential difference of 12 volts across it. What if the resistance is 4 ohms? 3 ohms?

Question 4

Suppose a circuit has a variable resistor connected to a battery. Sketch a graph of the current versus the resistance, as the resistor is adjusted from its maximum value to its minimum value.

Actually resistance is not constant for any conductor, but varies with temperature. In scientific work the Celsius (sometimes called centigrade) temperature scale is used. A temperature scale is made by taking advantage of the fact that a water and ice mixture stays at a constant temperature as long as some ice remains, and that boiling water at one *atmosphere* of pressure stays at a constant temperature until all the water has boiled away. The zero of the Celsius scale is defined as the ice point of water, and the "100" of the Celsius scale is defined as the boiling point of water at one atmosphere. The scale is then subdivided. Figure 5 shows a comparison between the Celsius scale and the more familiar Fahrenheit scale, and may be used for converting a temperature from one scale to the other. You should now do *Experiment 3, Relationship of Resistance to Temperature for a Conductor.*

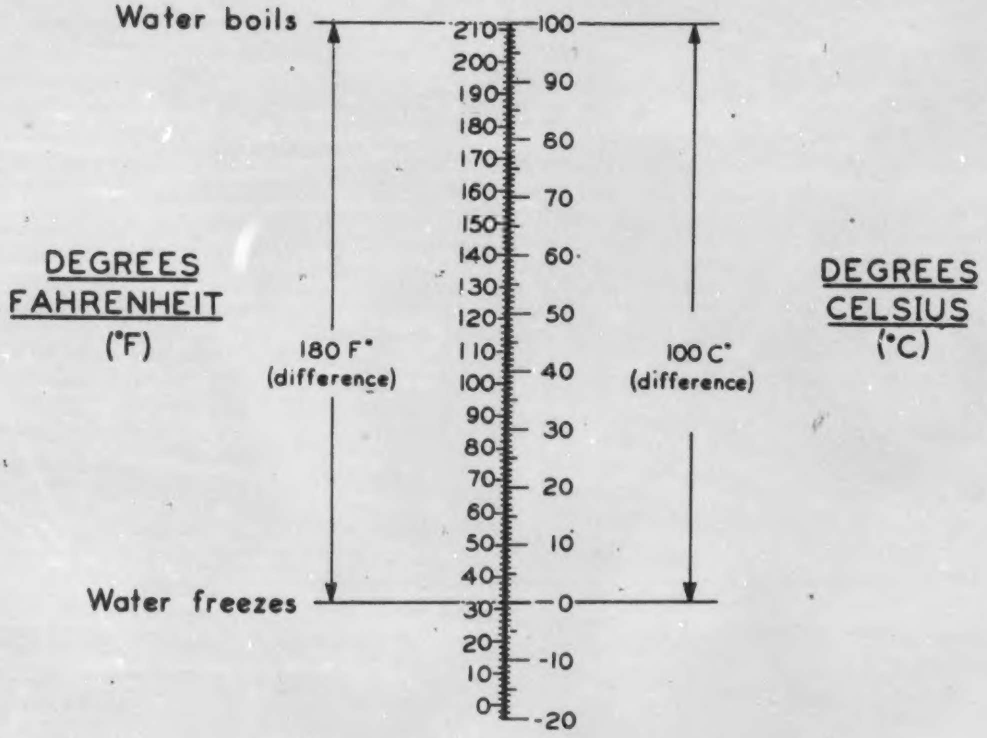

Water boils
Water freezes
DEGREES FAHRENHEIT (°F)
DEGREES CELSIUS (°C)
180 F° (difference)
100 C° (difference)
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
100
90
80
70
60
50
40
30
20
10
0
-10
-20

Figure 5

RELATIONSHIP BETWEEN THE FAHRENHEIT AND CELSIUS TEMPERATURE SCALES

By definition, a temperature of $0^{\circ}C$ corresponds to $32^{\circ}F$ and $100^{\circ}C$ to $212^{\circ}F$. Therefore, 100 Celsius degrees equals 180 fahrenheit degrees.

EXPERIMENT 3

THE RELATIONSHIP OF RESISTANCE TO TEMPERATURE FOR A CONDUCTOR

The purpose of this experiment is to determine the relationship of resistance to temperature for a conductor. The resistance will be measured with a Wheatstone bridge.

The diagram of a Wheatstone slide wire bridge is shown in Figure 1.

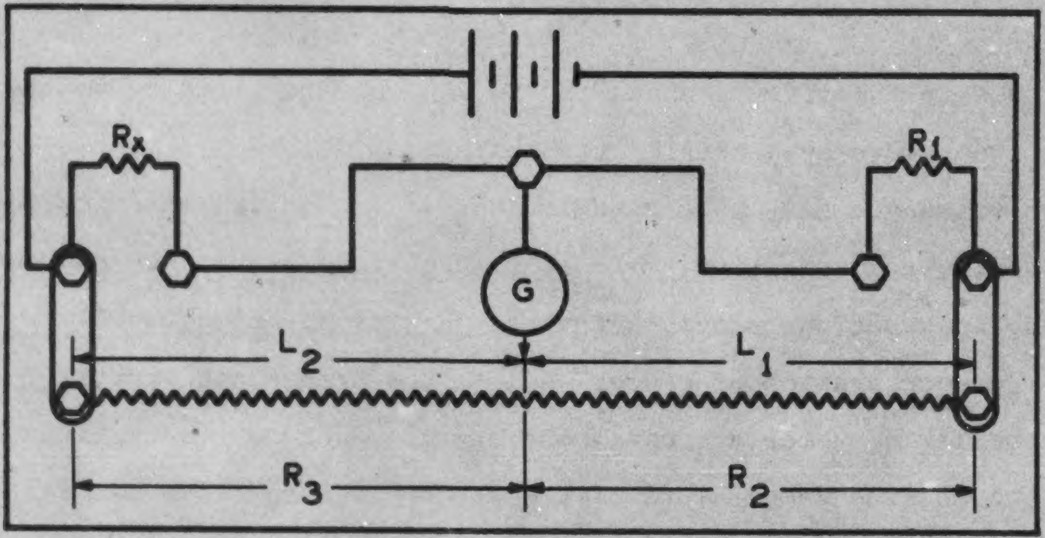


Figure 1

The values of three known resistances R_1, R_2, and R_3 are adjusted until there is no current through the galvanometer, (G).

When the current through the galvanometer is zero the bridge is said to be balanced. When the bridge is balanced the resistances are related as follows:

$$R_x = \frac{R_3}{R_2} R_1.$$

The slide wire is assumed to be uniform, so that the resistances R_2 and R_3 are directly proportional to the wire lengths L_1 and L_2. For the slide wire bridge, the unknown resistance R_x can therefore be expressed with the equation

$$R_x = \frac{L_2}{L_1} R_2.$$

Set up the circuit shown in Figure 1 and familiarize yourself with the bridge by measuring the resistance of the resistor of known value you have been given. (Note: The galvanometer in the bridge is very sensitive; make all connections cautiously and refer to any instructions provided for the Wheatstone bridge used).

Connect a spool of copper wire to the bridge and immerse it in a beaker of water at room temperature. Measure its resistance and the celsius temperature of the water. Record these values.

Next immerse the wire in ice water; measure the resistance, and record the temperature. Finally, immerse the wire in boiling water and wait a few minutes for it to reach the equilibrium temperature; then measure the resistance, and record the temperature.

Plot a graph of the resistance (in ohms) on the vertical axis and the temperature (in degrees celsius) on the horizontal axis. Over the temperature range studied, what is the relationship between resistance and temperature? If the relationship is linear, what are the values of the slope and vertical intercept? What are their units?

If you divide the slope by the vertical intercept, you get a constant which is a measure of the temperature dependence of the resistivity of the given material. What is the value of this constant for copper? This constant is called the temperature coefficient of resistance.

In Experiment 3 you found that resistance increases linearly with temperature for a conductor. This relationship may be expressed by the equation

$$R = R_o\ (1+\alpha T) \quad \text{(Relationship of Resistance and Temperature)} \quad (4)$$

where R is the resistance at a celsius temperature T, R_o is the resistance at 0° C, and α is a constant of the material called the temperature coefficient of resistance. The units of α are $1/^\circ C$.

Example Problem

Iron has a temperature coefficient of resistance, α, of $5.0 \times 10^{-3}/^\circ C$. Calculate the resistance of iron at 100° C if its resistance at 0° C is 1.0 ohm.

Solution

Given in the problem are

$$\alpha = 5.0 \times 10^{-3}/^\circ C,\ R_o = 1.0 \text{ ohm and } T = 100^\circ \text{ C}.$$

Substitution into equation (4) gives

$$R = 1.0 \text{ ohm } (1+5.0 \times 10^{-3}/^\circ C \times 100^\circ \text{ C}).$$

Multiplying inside the parenthesis gives

$$R = 1.0 \text{ ohm } (1+0.5) \text{ or}$$

$$R = 1.0 \text{ ohm} \times 1.5.$$

The value of resistance at 100° C is then

$$R = 1.5 \text{ ohm, or}$$

$$R = 1.5\ \Omega.$$

From this point on, the word ohm will be represented by the symbol Ω.

Problem 6

Copper has a temperature coefficient of resistance, α, of $4.0 \times 10^{-3}/^{\circ}C$. Calculate the resistance of a bar of copper at 100° C if its resistance at 0° C is 0.01 Ω.

Example Problem

A container of mercury has a resistance of 0.20 Ω at 0° C. When its temperature is raised to 200° C, the resistance becomes 0.236 Ω. What is the temperature coefficient of resistance for mercury?

Solution

Given in the problem are

$$R_o = 0.20\ \Omega,\ R = 0.236\ \Omega \text{ and } T = 200^{\circ}\ C.$$

Equation (4) must now be solved for α. Dividing both sides of equation (4) by R_o gives

$$\frac{R}{R_o} = 1+\alpha T.$$

Subtracting 1 from both sides yields

$$\frac{R}{R_o} - 1 = \alpha T.$$

Now dividing both sides of this equation by T and reversing sides,

$$\alpha = \left(\frac{R}{R_o} - 1\right)/T.$$

Substituting values into this equation yields

$$\alpha = \left(\frac{0.236\ \Omega}{0.20\ \Omega} - 1\right)/200^{\circ}\ C.$$

Dividing the resistances and canceling ohms gives

$$\alpha = (1.18 - 1)/200^{\circ}\ C.$$

Subtracting 1 and expressing the temperature in power of ten gives

$$\alpha = \frac{0.18}{2 \times 10^{2}} / {}^{\circ}C.$$

Dividing and rewriting the power of ten yields

$$\alpha = 0.09 \times 10^{-2}/{}^{\circ}C$$

or

$$\alpha = 0.9 \times 10^{-3}/{}^{\circ}C.$$

Problem 7

The resistance of a certain metal is 100 Ω at 0° C. If its resistance rises to 122 Ω when its temperature is raised to 60° C, what is the temperature coefficient of resistance for this material?

Question 5

A length of nichrome wire is connected across the terminals of a dry cell. After a short time, the wire gets quite hot. What happens to the current during the time the wire is connected?

The fact that resistance increases with temperature is employed in the design of recent ignition systems. A "ballast resistor" is placed in the circuit between the battery and the primary of the ignition coil. The ballast resistor relies upon the change of resistance with temperature to improve the ignition system performance. The detailed function of the ballast resistor will be explained later in the module, when you are more familiar with the theory of the ignition system.

III. ELECTROMAGNETIC INDUCTION

The purpose of the automobile ignition system is to produce the thousands of volts necessary to force a spark across the spark plug gap at the correct time to ignite the fuel-air mixture in the cylinder, when only 6 to 12 volts are available at the battery. This voltage jump is produced in the ignition coil. The ignition coil is really two coils; one in the primary circuit and one in the secondary circuit. The current in the primary windings of the coil is interrupted by the opening of the contact points. When this interruption occurs, a large voltage is "induced" in the secondary windings. This effect is due to what is known as electromagnetic induction. To understand electromagnetic induction, it is first necessary to understand the magnetic effects of an electric current.

Naturally occuring magnetic materials, in the form of permanently magnetized pieces of a mineral known as lodestone, were known to the early Greeks. Furthermore, the similarity between magnetism and static electricity was noted quite early in history. Both forces seemed to reach out through empty space to attract objects. A piece of amber, when rubbed with fur, would attract many small objects, and a magnet would attract pieces of iron. Despite this similarity, no one was able to construct a successful explanation of the connection between the two forces until early in the last century. At that time, scientists were able to show that an electric current can exert a magnetic force on a small nearby magnet. They had discovered that an electric current produces magnetism. Modern science regards all magnetic effects as resulting from electric currents. Even permanent magnets derive their magnetism from electric charges moving in atoms.

Since we cannot see magnetism, how do we know when it is present? You know that the earth has magnetism by its effect on a compass needle. We could use a compass or some other permanently magnetized material as an indicator of magnetism, or what we call a *magnetic field*. Hans Christian Oersted, in 1820, discovered the magnetic interaction between a current-carrying wire and a magnet. It is easy to demonstrate that if a magnetic compass is placed near a wire which is intermittently connected to a battery, the compass needle will deflect a small amount each time. This deflection indicates that while there is a current through the wire, a magnetic field is produced which exerts a force that acts on the compass needle to make it deflect or change its state of motion. To investigate magnetism, you should now do *Experiment 4, Magnetic Fields and Electromagnetic Induction.*

EXPERIMENT 4

ELECTROMAGNETISM (A QUALITATIVE INVESTIGATION)

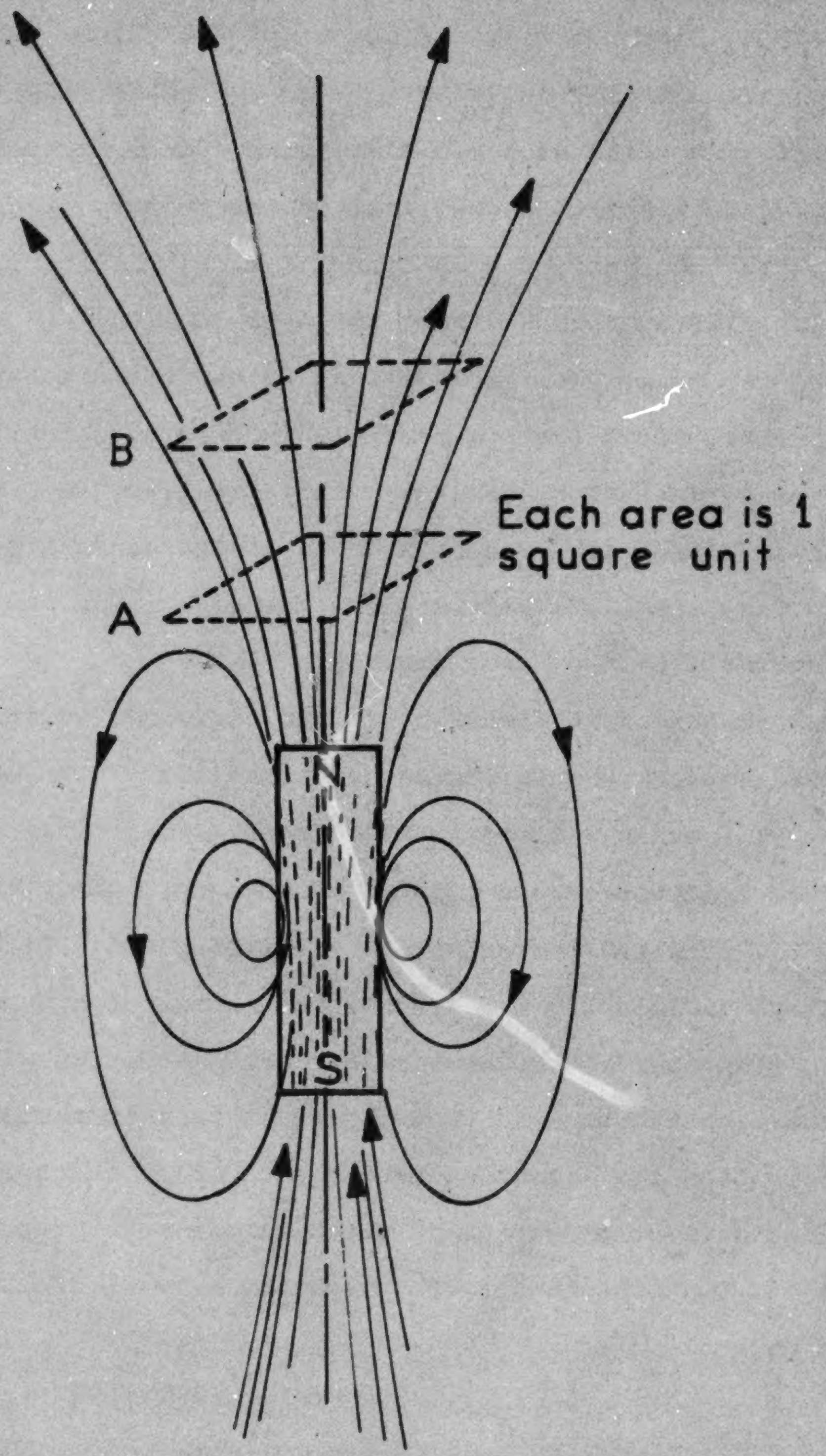
Most of us are familiar with small permanent magnets. Their ability to attract iron nails or filings is a commonly observed phenomenon. An elementary principle of magnetism is that there are two poles, and that like poles repel and unlike poles attract. A magnet can attract objects like paper clips without coming into physical contact with them. The effect of a magnet reaches out across space, even through a vacuum, to exert a force. The region of influence surrounding a magnet is called the *magnetic field*.

The magnetic field produced by a magnet cannot be seen, but its presence can be demonstrated by sprinkling iron filings on a glass sheet placed over a bar magnet. After gently tapping the glass sheet, the filings will arrange themselves in a pattern which is representative of the field surrounding the magnet.

Do the following demonstration. Place a bar magnet under a plastic or glass sheet. Sprinkle iron filings on the sheet and gently tap it. Note how the filings arrange themselves, and sketch the resulting pattern. Where do lines formed by the filings tend to be most concentrated? Disturb the pattern several times by tapping the sheet. After each tapping, do the filings arrange themselves in essentially the same pattern?

The looping pattern of the iron filings is a macroscopic representation of the magnetic field lines (flux lines) surrounding the magnet. The number of the lines per unit of area is a measure of the magnetic induction.

The concentration of iron filings is greatest near the poles of the magnet, indicating the concentration of magnetic lines is greatest there. The magnetic induction is therefore strongest near the poles. As we get further from the poles the magnetic lines spread out so that the number of lines per unit area decreases. The magnetic induction therefore decreases. This effect is shown in Figure 1.


B
Each area is 1 square unit
A
N
S

68

Figure 1

The magnetic induction decreases as we go from surface A to surface B of Figure 1, and the number of flux lines per unit area diminishes. Theoretically these ever expanding loops reach out to infinity, but the magnetic flux lines spread apart rapidly with distance from the magnet. Since the magnetic induction depends on the concentration of lines of flux, the induction falls off rapidly with distance from a magnet.

The arrangement of iron filings in the pattern is because the permanent bar magnet temporarily induces the iron filings to become small magnets themselves. These small magnets behave individually much like a compass does in the earth's magnetic field. They align themselves along the directions of the magnetic field surrounding the bar magnet.

Do magnets exert forces on moving charges? To answer this question, perform the following demonstration. Turn on the oscilloscope and obtain a trace on the screen. This trace is due to a beam of electron current moving through the tube. The electrons strike the sensitive screen where their energies excite the screen to radiate visible light. Bring a north pole of a magnet near the oscilloscope. Does the beam deflect? Note the direction. Turn the magnet around so that the south pole is nearest the oscilloscope. Does the direction of the deflection change? Does the amount of deflection depend on the distance between the magnet and the beam? Does the amount of deflection depend on the orientation of the magnet?

Next, suspend a wire coil as shown in Figure 2.

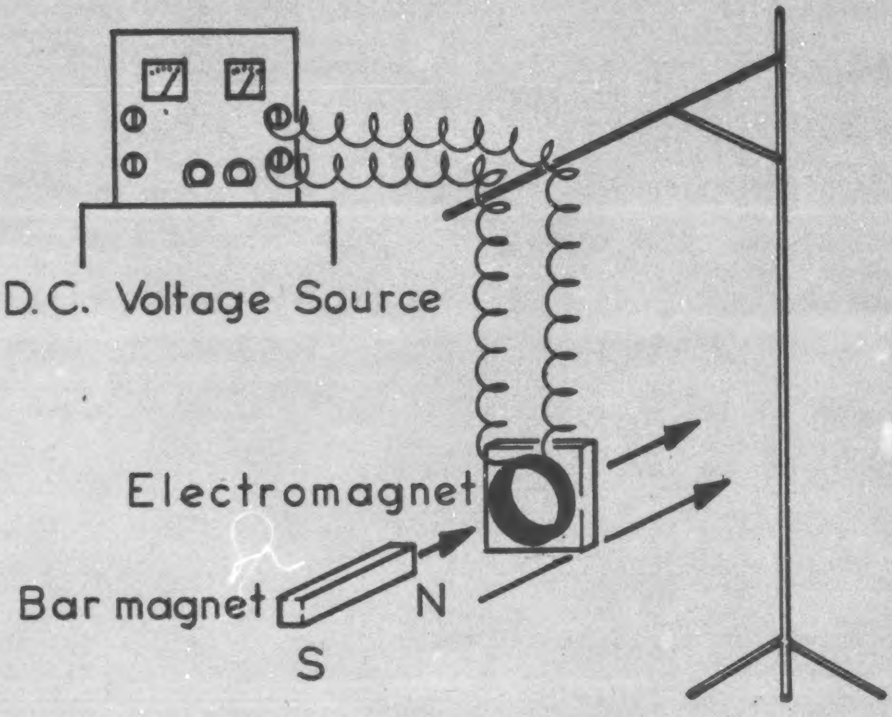


Figure 2

Pass a current of 1.5 amperes through the coil. Bring the north pole of a magnet near the axis of the coil. Does the magnet exert a force on the coil? Use a small compass, and note whether the coil seems to have a north and south pole on opposite sides. Does the current carrying coil seem to act as a magnet? Reverse the direction of current by interchanging the current leads at the power supply. Does the magnetic polarity of the coil reverse?

Insert the cardboard sheets through the center of a coil like the one used above and support the sheets with something. Adjust the current again to about 1.5 ampere. Sprinkle iron filings over the sheet. Tap the sheet, and describe the pattern produced. Does the pattern resemble that produced by the bar magnet?

The drawings of the field surrounding a bar magnet and the coil of wire should be carefully compared. Ignore both the coil and the bar magnet, and examine just the fields they produce.

We should notice that the field patterns in each case are of the same character. This result means that a bar magnet and a current-carrying coil should interact, and repel or attract each other, much in the same fashion as the interaction between two bar magnets. All the interactions between a coil and a bar magnet arise because the field generated by each is alone responsible for the interactions. This result suggests that the fields surrounding current-carrying wires or bar magnets act as agents through which the current in the coil can interact across space with the magnet. Are moving charges (current) the source of magnetic fields? It is believed at present that all magnetic phenomena arise from charges in motion. What charges are moving within the bar magnets? They must be the atomic particles within the metal bar. These "atomic currents" are localized, but the effects of the vast number of "atomic currents" add to produce the large scale external field surrounding a magnet. It is these currents which interact across space with the current carried by the wires of the coil. It is worthwhile to conclude that magnetic fields can exert forces only on charges in motion.

Thus far we have investigated magnetic fields which are steady and are the result of steady currents. What happens when the magnetic induction or the number of magnetic lines of flux linking a coil of wire changes with time? Let us investigate this question.

The arrangement for this investigation is shown in Figure 3.

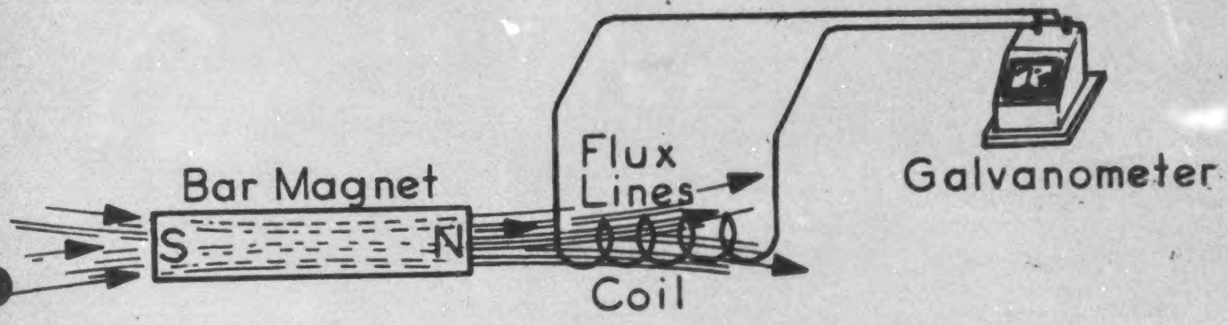


Figure 3

Place the bar magnet inside the coil. When the magnet is at rest, there is no current through the galvanometer. Quickly remove the magnet from the core of the coil. Does the galvanometer deflect? Note the direction, if it does. Quickly insert the magnet into the coil. Does the galvanometer deflect in the opposite direction? Slowly move the bar magnet in and out of the coil. Does the amount of current depend on the time rate at which the field changes?

Keep the magnet fixed and move the coil rapidly toward and away from the magnet. Do you observe similar effects?

Since we have observed that the magnetic fields produced by bar magnets, and those produced by a coil of wire, both have the same basic characteristics, a current-carrying coil should serve as well as a bar magnet for producing flux lines linking a second coil having no source of current. Furthermore, since the field depends on the current, we can increase or decrease the number of flux lines by increasing or decreasing the current through one of the coils. This arrangement is shown in Figure 4.

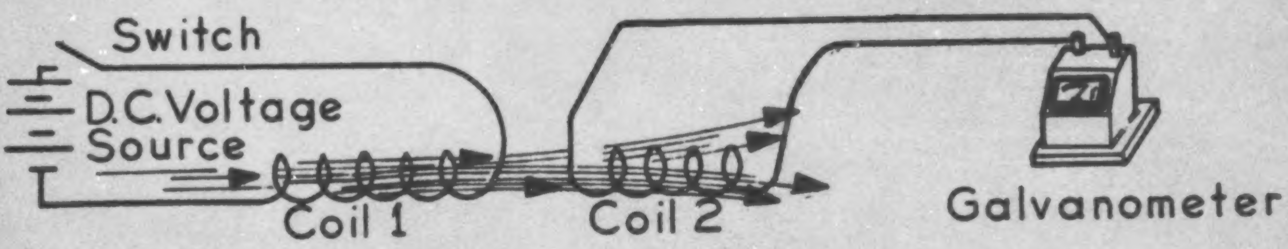


Figure 4

Place the coils so that their axes are in a line and the coils are as close together as possible. Close the switch to create the field, and note if the galvanometer deflects. Open the switch to collapse the field. Does the galvanometer deflect in the opposite direction? Could we conclude that the direction of current depends on whether the field is building up or collapsing.

It is only a potential difference which can produce a current. We should therefore conclude that *a changing magnetic induction generates a potential difference capable of producing currents.*

This electromotive force (EMF) drives a current around the circuit. These results can be generalized by means of *Faraday's law: the induced voltage (EMF) in a circuit is equal to the rate of change of magnetic flux linking the circuit.*

Does the amount of voltage induced depend on the number of turns of wire in a coil? Each turn has induced in it a voltage which is proportional to the *rate of change* of magnetic flux. The total voltage induced across the coil is the number of turns N times the voltage developed per turn. Does the amount of flux linking the two coils increase when an iron core is placed between the two coils? Let us examine this situation. Use the arrangement shown in Figure 4.

Before inserting the U shaped iron core into the coils, interrupt the current and note the maximum current developed. Also note whether any sparks appear at the contacts of the switch. Insert the U shaped iron core, and interrupt the current by opening the switch. Is the maximum galvanometer deflection larger? What does this observation indicate about the magnetic coupling between the two circuits?

Before the interruption of the current, there was a magnetic field surrounding the coils. The field ceases to exist when the current is stopped.

The opening of the switch causes the current to cease very rapidly resulting in a very rapid decrease in the magnetic induction field. The circuit containing the voltage source also experiences this rapid change of magnetic flux. In this circuit a large self induced voltage is developed. As a result, a spark arcs across the switch.

Suppose we wish to create sparks that will jump across air gaps, such as the sparks which jump across the electrodes in an automobile spark plug. These sparks require a large voltage, roughly in the neighborhood of 15,000 volts, for a normal spark plug. Perform the following demonstration.

As you learned earlier, when two coils are placed close to each other, any increase or decrease in current through one coil will induce a voltage in the second coil. This is the basic principle of operation of an auto ignition coil. The ignition coil (Figure 5) is made up of two sets of windings wound around a core of soft iron strips which enhance the coupling of the magnetic flux lines between the two coils.

One coil is called the primary. It consists of a few hundred turns (150-250) of No. 20 gauge wire. The secondary is made up of several thousand turns (15,000-25,000) of very fine No. 40 gauge wire. Each turn of wire, both in the primary and in the secondary, is prevented from making contact with other turns by means of insulating material.

The arrangement for this investigation is shown in Figure 5.

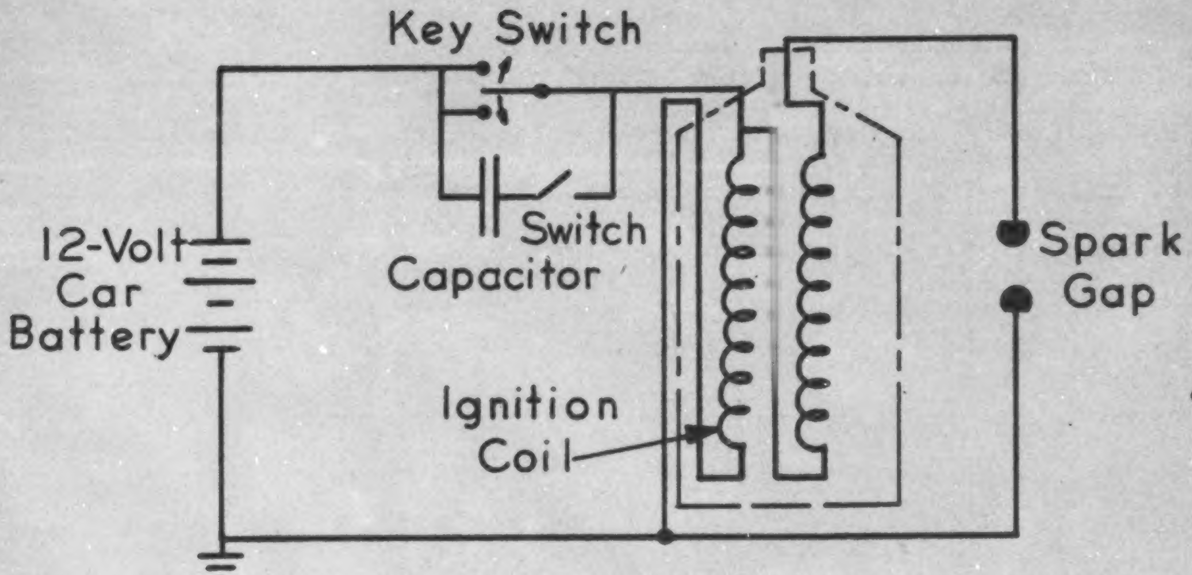

Key Switch
Switch
Capacitor
12-Volt
Car
Battery
Ignition
Coil
Spark
Gap

Figure 5

Close the switch-key and allow the current to build up in the primary. The current build-up requires less than 0.01 second. The maximum current in the circuit is determined by the resistance of the primary coil. When the current is maximum, the magnetic field is also at a maximum. Tap the switch-key to open the circuit and rapidly collapse the magnetic induction field. Do you notice sparks arcing across the spark gap? Are there sparks arcing across the switch? The arcing across the key in the primary circuit can be prevented by using a capacitor. The capacitor (sometimes called a condensor) is an electrical component which stores electric charge. When the switch-key opens, the primary has a high induced voltage, so that arcs are produced across the contact points of the switch.

With the capacitor placed across the contact points of the switch, the primary current flows into the capacitor, charging it up, instead of arcing. Insert the capacitor across the points and determine if the arcing ceases.

Now that you know how to detect the presence of a magnetic field, how can we define it? We are free, of course, to define it in any manner we like. It is common practice to define quantities in terms of effects that we can observe. In 1825, Andre' Ampere showed that the magnetic force on a current-carrying wire increases when the current in the wire increases, and that this force also increases when the magnetic field (called induction) increases. This relationship may be expressed in the following form:

$$F = BI\ell \qquad (5)$$

where F is the force (push or pull), I is the current in the wire, ℓ is the length of the wire, and B is called the *magnetic induction*. It turns out that equation (5) is true only when the current is at right angles to the magnetic induction. No force results when the current and magnetic induction are in the same direction. You saw this directional property of the force when you changed the relative orientation of the wire and compass in Experiment 4. Equation (5) may be used as the defining equation for the magnetic induction. In a given system of units,

$$\boxed{B = \frac{F}{I\ell}.} \text{ (definition of magnetic induction)} \qquad (6)$$

If F is in newtons, represented by the letter "N", I is in amperes (A), and ℓ is in meters (m), then the unit of magnetic induction becomes a newton/A-m, called a tesla. The tesla is represented by the letter, "T".

Example Problem

Determine the force on a 10 cm length of wire which is at a right angle to the direction of a magnetic field with a magnetic induction of 0.2 tesla when the current in the wire is 5 A.

Solution

Given are

$$B = 0.2 \text{ tesla}, \ I = 5 \text{ A and } \ell = 10 \text{ cm} = 10^{-1} \text{ m}.$$

Substituting into equation (5) yields

$$F = (0.2 \text{ newton/A-m})(5 \text{ A})(10^{-1} \text{ m}),$$

or

$$F = (0.2)(0.5 \ \frac{\text{newton}}{\text{A-m}})(\text{A-m}).$$

The solution is then

$$F = 0.1 \text{ newton}.$$

Problem 8

What force would be exerted on a 3 cm length of wire with a current of 1 A that is at right angles to a magnetic field with a magnetic induction of 0.08 tesla?

Example Problem

Determine the magnetic induction between the poles of a magnet if a 5 cm length of wire with 0.5 A current in it experiences a force of 0.003 newton when the wire is perpendicular to the direction of the induction field.

Solution

Given are

$F = 0.003 \text{ newton} = 3 \times 10^{-3} \text{ newton}, \ I = 0.5 \text{ A} = 5 \times 10^{-1} \text{ A},$

and

$$\ell = 5 \text{ cm} = 5 \times 10^{-2} \text{ m}.$$

Substituting into equation (6) gives

$$B = \frac{3 \times 10^{-3} \text{ newton}}{(5 \times 10^{-1} \text{ A})(5 \times 10^{-2} \text{ m})}.$$

Canceling powers of ten and simplifying gives

$$B = 0.12 \text{ newton/A-m} = 0.12 \text{ tesla}.$$

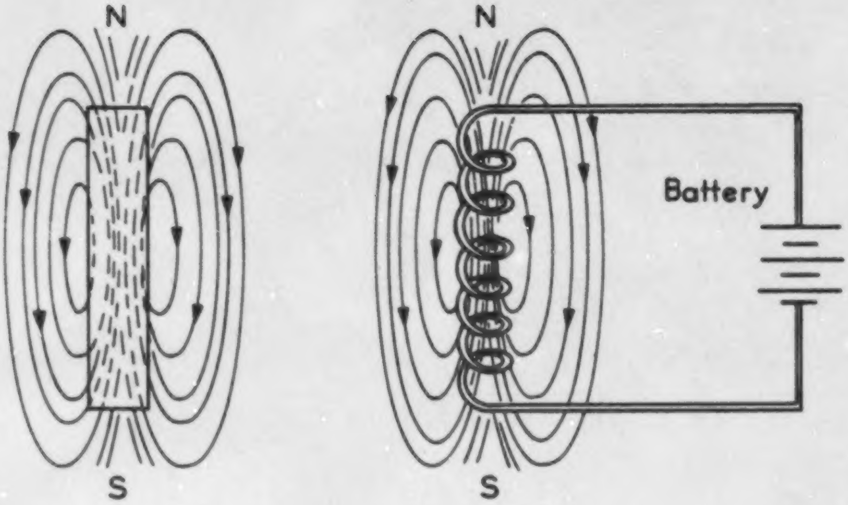
Problem 9

Find the magnetic induction which exerts a force of 0.06 newton on a 7 cm length of wire if the wire has a current 0.3 A. The wire is perpendicular to the magnetic field.

Question 6

A current-carrying wire of given length is placed at right angles to a magnetic field. The wire gets hot, and its resistance therefore increases. Precisely what happens to the magnetic force on the wire?

A magnetic field is invisible, but it is often envisioned as a set of curved lines, as shown in Figure 6.



Bar Magnet

Coil of wire

Figure 6

Remember, however, that the lines do not actually exist. They are used as a model to aid our understanding of magnetism. When using these field lines to picture a magnetic field, the direction of the magnetic force at any point in the field is indicated by the direction of the lines. The strength of the force is shown by the density of the lines. In other words, the closer together they become, the stronger the magnetic induction.

As shown in Figure 6, the lines are closer together at the ends of the magnets than they are at any other place around the magnet. This means that the magnetic induction is strongest at the ends or poles. Magnetic field lines are continuous, closing on themselves. With a coil, the lines loop through the center of the coil; whereas, in a bar magnet, they close inside the magnet.

When a piece of iron is inserted through the center of a coil, it increases the magnetic induction in that region, as if the field lines crowd together to go through the metal. Because the lines always close on themselves, forming complete loops, scientists visualize them as lines of flow of what is called magnetic flux. This magnetic flux could be indicated by the total number of magnetic field lines. Then the magnetic induction can be looked upon as a flux density. That is, the more lines of flux crossing a given area, the greater the magnetic induction in that area. If we are to take the flux density, or number of lines per unit area, and multiply it by the area, we would obtain the total number of lines of flux which are contained in that area. Since we can't count the number of imaginary lines, but we do have a definition of magnetic induction, this will be our definition of magnetic flux. If we let A represent the area perpendicular to the direction of the magnetic induction, B, then we define the magnetic flux, Φ, as

$$\boxed{\Phi = BA.} \quad \text{(Definition of Magnetic flux)} \qquad (7)$$

When B is in tesla (newton/A-m), as before, and A is in m^2, then the units for magnetic flux become N-m/A. As is often the case, a new unit is defined in honor of a person who contributed greatly to this area of science. Such a person was Wilhelm Weber and the unit of magnetic flux is therefore called the Weber, and represented by "Wb".

We have seen that there are at least two ways to consider magnetic fields. Both of these ways are by means of an effect of this field. One is through the force which a magnetic induction exerts on a current-carrying wire, and the other is the model of the density of flux lines which must exist around the wire or magnet. In the case of a changing magnetic field in the vicinity of a coil of wire, which is the situation in the auto ignition system, it is the latter model which will be most useful. For this reason we rearrange equation (7) so that the magnetic induction may be written as a flux density

$$\boxed{B = \Phi/A.} \quad \text{(Flux density expression for Magnetic Induction)} \qquad (8)$$

The units of magnetic induction or flux density, when expressed this way, may be written as webers/m^2. If one substitutes dimensions into the definition of a weber, he finds that

$$1\ \text{weber}/m^2 = 1\ \text{newton/amp-m} = 1\ \text{tesla}.$$

Thus B may be expressed in two equivalent units, depending upon whether we are interested in the force it produces or in the number of lines of force which we associate with it.

Example Problem

What is the magnetic flux in webers across an area of 10 m^2, if the magnetic induction (flux density) is 1.5 tesla?

Solution

Given are

$B = 1.5$ tesla $= 1.5\ Wb/m^2$, and $A = 10\ cm^2 =$
$10\ cm^2 = 10 \times 10^{-4}\ m^2 = 10^{-3}\ m^2$.

Substituting into equation (8) we get

$$\Phi = (1.5\ \text{Wb/m}^2)(10^{-3}\ \text{m}^2),$$

or

$$\Phi = 1.5 \times 10^{-3}\ \text{weber.}$$

Problem 10

What is the magnetic flux through an area of 15 cm^2, if the magnetic flux density is 0.75 tesla?

Example Problem

Calculate the magnetic induction or flux density through an area of 1 cm^2 ($10^{-4}\ \text{m}^2$), if this area contains 5×10^{-5} webers of magnetic flux. Give your answer in tesla.

Solution

Given are

$$\Phi = 5 \times 10^{-5}\ \text{webers and } A = 1\ \text{cm}^2 = 10^{-4}\ \text{m}^2.$$

Substituting into equation (8) gives

$$B = \frac{5 \times 10^{-5}\ \text{webers}}{10^{-4}\ \text{m}^2}\ .$$

Simplifying the powers of ten yields

$$B = 5 \times 10^{-1}\ \text{webers/m}^2,$$

or

$$B = 0.5\ \text{tesla}$$

or

$$B = 0.5\ \text{T.}$$

From this point on, "T" will be used for "tesla", and Wb will be used for Webers.

Problem 11

Calculate the average magnetic induction over an area of 50 cm^2, if this area contains 1.5×10^{-2} Wb of magnetic flux.

Question 7

The density of flux lines is a measure of magnetic induction. Why must it be impossible for two or more such lines to cross each other (What is the density of lines at the point of intersection?)?

Both the magnetic flux and the magnetic induction from a coil are due to the current in the coil. In general, the formula for the magnetic induction due to a current depends in quite a complicated way on the geometry of the situation and on the substances in the neighborhood of the current. However, in air or in a vacuum, the magnetic induction at any point, and therefore the magnetic flux through any area, is proportional to the current, that is,

$$B \propto I, \text{ and}$$

$$\Phi = AB \propto I. \qquad (9)$$

Knowing that an electric current could produce magnetic fields, scientists tried for several years to reverse the process, and produce an electric current from magnetic fields. In 1831, the English physicist Michael Faraday found that whenever lines of magnetic flux change in a circuit, a voltage, or EMF, is induced in it. This process is called electromagnetic induction. In a loop of wire, as shown in Figure 7, the EMF induced is equal to the time rate of change of the magnetic flux.

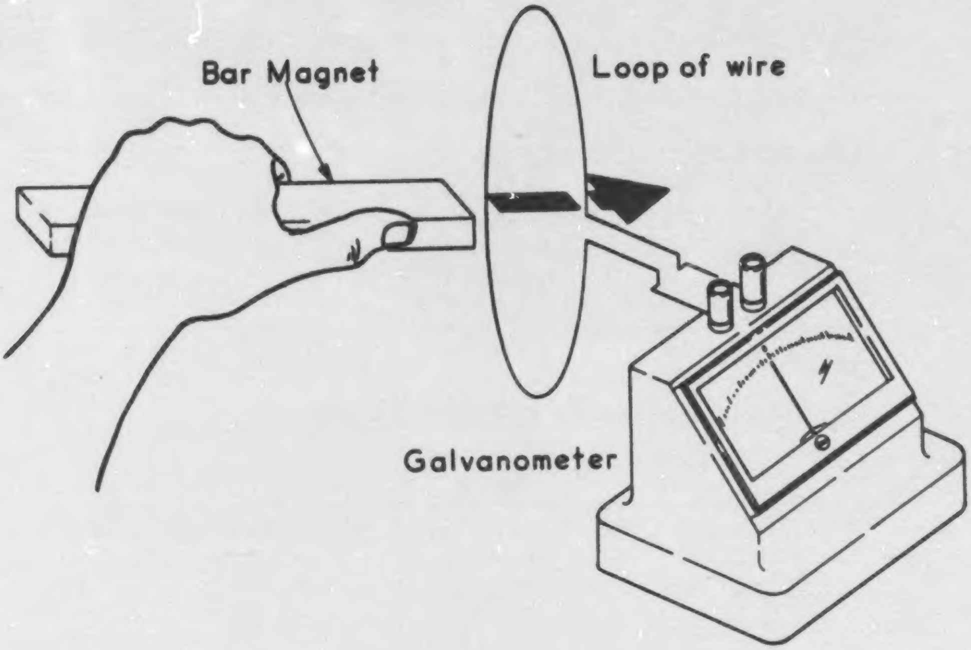


Figure 7

If $\Delta\Phi$ represents the change in flux through the coil in the small time Δt, the magnitude of the induced EMF is

$$\boxed{E = \frac{\Delta\Phi}{\Delta t}}, \quad \text{(Faraday's Law of Electromagnetic Induction)} \quad (10)$$

where Φ is in webers and t is in seconds. This equation is known as Faraday's Law. If there are N turns in the coil, the same voltage is induced in each turn, and these voltages add, so that

$$\boxed{E = N\,\frac{\Delta\Phi}{\Delta t}}. \quad \text{(Faraday's law for a coil of N turns)} \quad (11)$$

It can be seen from equation (11) that since N is a dimensionless number, and E is in volts, 1 volt = 1 Wb/second.

Example Problem

What would be the induced EMF in the secondary winding of the ignition coil of an automobile, if it contains 15,000 turns and the magnetic flux enclosed by the coil changes by 3×10^{-4} Wb in 0.6 milliseconds?

Solution

Given are

$$\Delta\Phi = 3 \times 10^{-4} \text{ Wb}, \; N = 15{,}000,$$

and

$$\Delta t = 0.6 \text{ milliseconds} = 6 \times 10^{-4} \text{ seconds}.$$

Substituting these values into equation (11) gives

$$E = (1.5 \times 10^{4})\left(\frac{3 \times 10^{-4} \text{ Wb}}{6 \times 10^{-4} \text{ seconds}}\right),$$

which simplifies to

$$E = \frac{1.5 \times 3}{6} \times 10^{4} \text{ Wb/seconds}.$$

Performing the indicated arithmetic gives

$$E = 7.5 \times 10^{3} \text{ Wb/seconds},$$

and since 1 Wb/second = 1 volt,

$$E = 7500 \text{ volts}.$$

Problem 12

If the magnetic flux enclosed by a 200 turn coil changes by 2×10^{-3} Wb in 1 second, what will be the induced EMF in the coil?

Question 8

A bar magnet held vertically is dropped through a single loop of wire. The loop is held in a horizontal plan, and the magnet passes right through the center. Taking into account the fact that the magnet speeds up as it falls, sketch a graph of current versus time in the loop.

The change in flux enclosed by a coil may be produced in several ways. A relative motion between the coil and the magnetic field can produce a changing flux. In the ignition coil, the flux changes simply because the primary current changes. When the flux is proportional to the current, a change in flux, $\Delta\Phi$, will be proportional to the change in current, ΔI. Relationships (9) and (11) can be combined to show that

$$E = N \frac{\Delta\Phi}{\Delta t} \propto \frac{\Delta I}{\Delta t} . \qquad (12)$$

It is important to remember that the induced EMF can be in the coil carrying the changing current itself, and it can be in a nearby coil. The magnetic flux through each will be changing. The ignition coil is actually two coils, the primary of about 200 turns and the secondary of about 15,000 turns. The primary is used to produce the changing magnetic field. Because of the large difference in turns between the primary and secondary coils, the secondary coil is at a much higher voltage than the the primary coil. The constant of proportionality in equation (12) is called the *self inductance*, L, if we are considering the EMF a coil induces in itself. Thus, when the flux is proportional to current,

$$\boxed{E = -L \frac{\Delta I}{\Delta t}} \text{ . (Voltage produced by an inductance) (13)}$$

The minus sign in equation (13) indicates that the induced EMF always opposes the change in current: if the current decreases, E tends to increase it, and if the current increases, E tends to decrease it. The units of inductance are called henries (1 henry = 1 volt-second/A). Similarly, if the flux is proportional to current for two coils in close proximity, each coil induces an EMF in the other, and these induced EMF's are related by the following equations:

$$E_2 = -M \frac{\Delta I_1}{\Delta t} \qquad (14a)$$

or

$$E_1 = -M \frac{\Delta I_2}{\Delta t} . \qquad (14b)$$

Equation 14a and 14b are special cases of a general *reciprocity theorem* in electric circuit theory. The constant M is called *mutual inductance*. The same constant, M, is used for calculating the EMF produced in either coil by a changing current in the other. For the two coils, a changing current in the first (ΔI_1) induces a voltage in the second (E_2) but the same changing current in the second (ΔI_2) would induce the same voltage in the first (E_1).

As already indicated, the concepts of self-inductance and mutual inductance can be used as shown in equations 13 and 14, only if the flux is proportional to the current. For coils having a core of air and many other substances, the flux *is* proportional to the current. However, when the core material is iron, or some other *ferromagnetic* material, and the core is closed around the coil, the flux may no longer be proportional to the current. Except for small currents in a coil around such a core, no fixed value of inductance or mutual inductance exists. How, then, can we use the *concepts* of inductance or mutual inductance when we are dealing with the ignition coil, which has an iron core?

All materials, whether solid, liquid, or gas, are to some extent magnetic. When placed in a magnetic field, a substance which aligns at right angles to the field is called *diamagnetic*, and one that aligns itself parallel with the field is called *paramagnetic*. In both of these cases, the strength of the magnetic torque ("twisting force") is small. When the aligning torque is very strong, the substance is called *ferromagnetic*. Iron is the best example of a ferromagnetic substance.

When soft iron is used as a coil core, it increases the density of flux produced by the coil. This is because tiny pieces of iron (called domains) are themselves little magnets, and when these domains are in the presence of the magnetic field of the coil, they align themselves with that field, thereby adding their magnetism to that produced by the coil. This added magnetism is enormous for iron, often increasing the field by many times what the field would be for an air core.

If these domains align with the field in proportion to the coil current, the simple inductance and mutual inductance definitions are still appropriate. For a coil having a closed core, shaped like a ring, most domain changes occur for small applied fields, the effects decreasing as the applied field gets large. For very large currents, most domains are aligned, and no further magnetism can be produced by the core. The core is then said to be *saturated*. Figure 8 shows a graph of what we call the *total* *magnetic flux* linkage for a coil with a soft iron, closed core. This *total* magnetic flux linkage is the actual flux multiplied by the number of turns. The slope of this graph, for a certain current, is the inductance of the coil. Figure 9 shows the same relationship, but for an expanded horizontal scale, so that the total flux linkage can be determined for small currents. Notice that the graph of Figure 9 is essentially a straight line from about -.05 A to +.05 A; so that in this region the slope, and therefore the inductance of the primary, is constant.

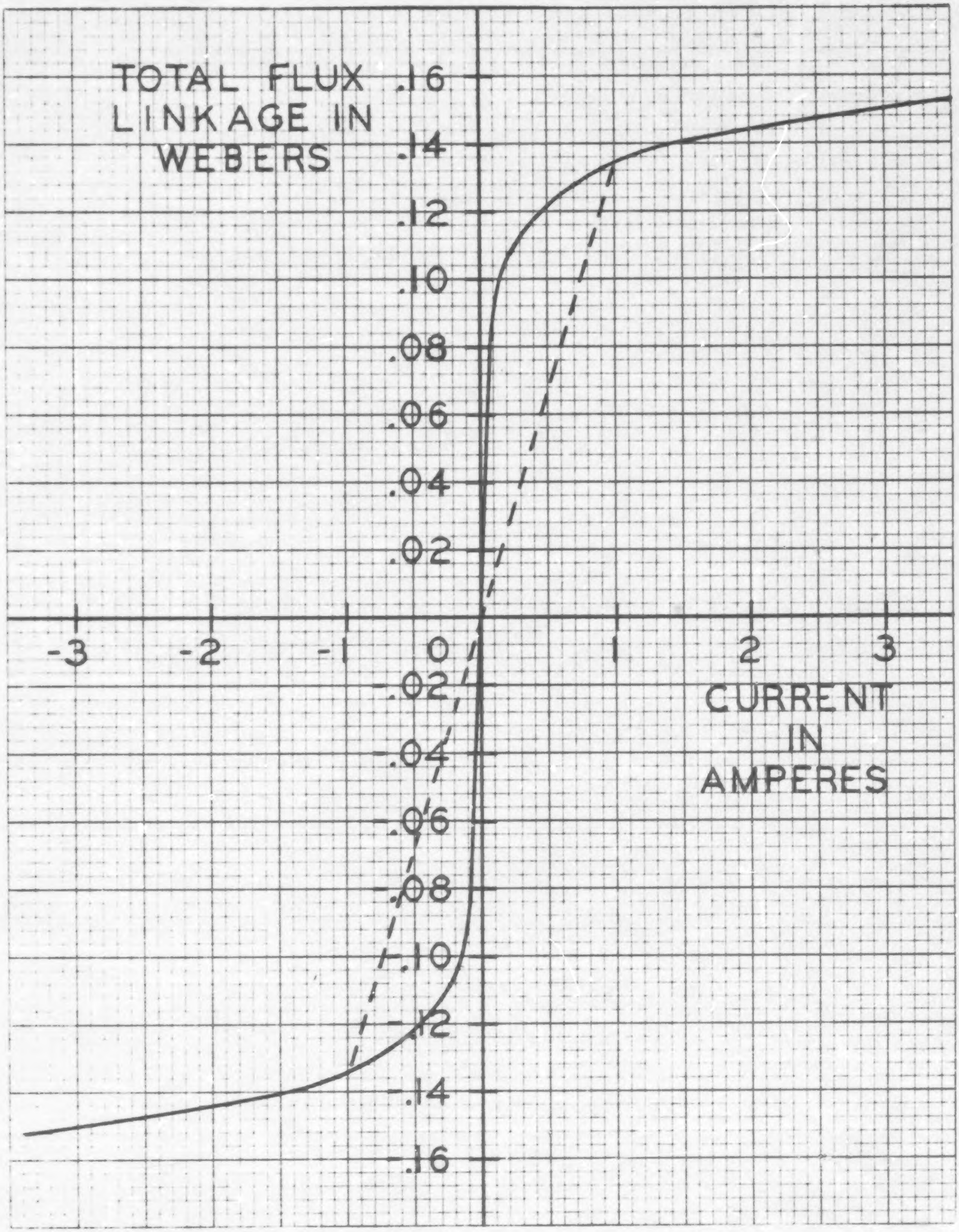

TOTAL FLUX LINKAGE IN WEBERS
.16
.14
.12
.10
.08
.06
.04
.02
-.02
-.04
-.06
-.08
-.10
-.12
-.14
-.16
-3
-2
-1
0
1
2
3
CURRENT IN AMPERES

Figure 8

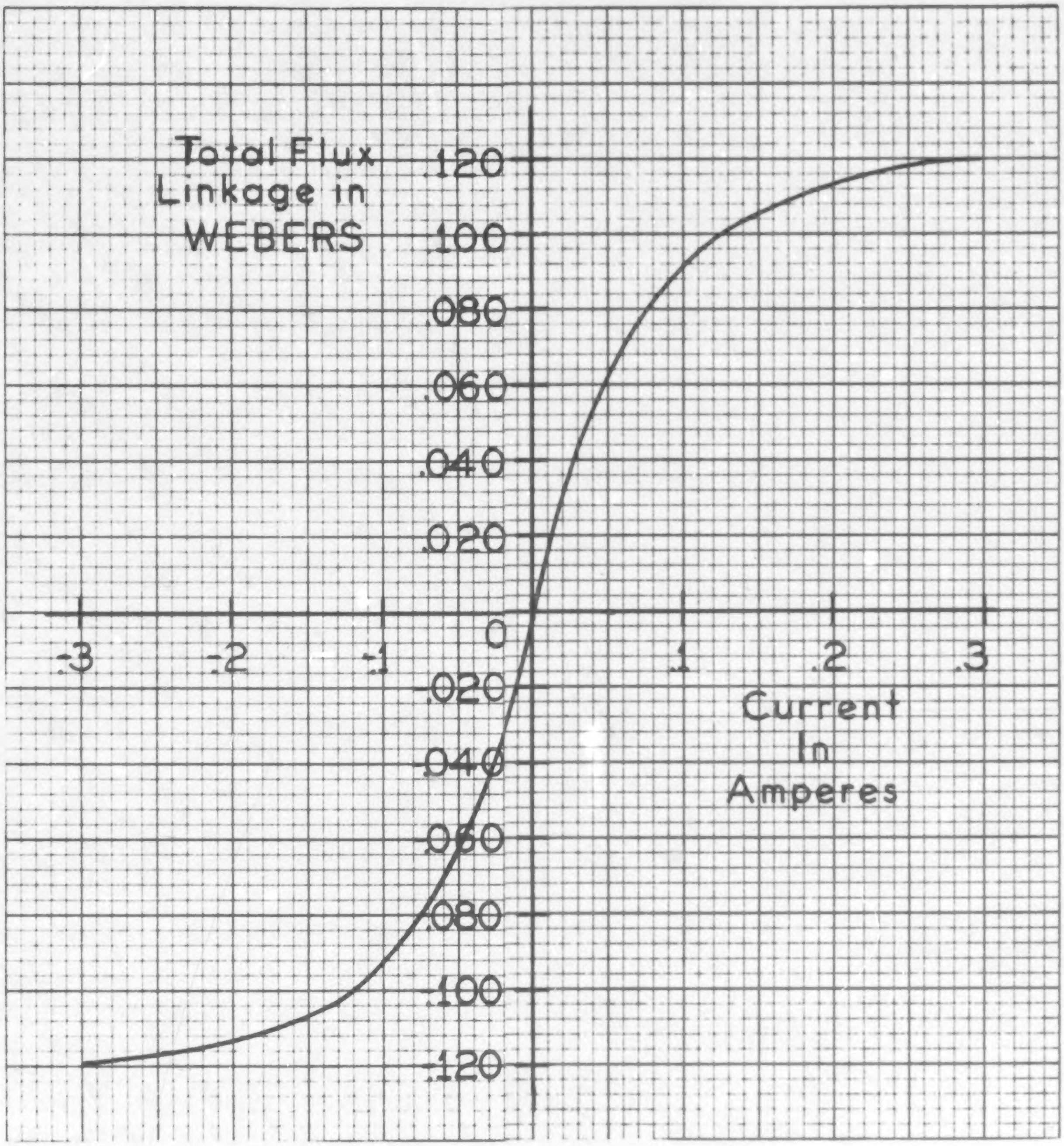

Total Flux
Linkage in
WEBERS
.120
.100
.080
.060
.040
.020
0
-.020
-.040
-.060
-.080
-.100
-.120
-.3
-.2
-.1
.1
.2
.3
Current
In
Amperes

Figure 9

Example Problem

For currents from -.05 to +.05 A, what is the self-inductance of the iron-core coil, for which Figure 9 is a graph of total magnetic flux linkage versus current?

Solution

The slope of this graph is the self-inductance. For a "rise" of 0.060 Wb from the origin, there is a "run" of .05 A. We have

$$L = \frac{\text{rise}}{\text{run}} = \frac{6 \times 10^{-2}\ \text{Wb}}{5 \times 10^{-2}\ \text{A}},$$

or

$$L = 1.2\ \text{Wb/A}.$$

Recalling that, 1 Wb = 1 volt-second, we have

$$L = 1.2\ \text{volt-second/A}.$$

But 1 henry = 1 volt-second/A; therefore,

$$L = 1.2\ \text{henry}.$$

Problem 13

For a current of 3 A, what is the self-inductance of the coil for which Figure 8 is a graph of total magnetic flux linkage versus current?

Question 9

A coil of wire has a certain inductance. When a piece of soft iron is placed near the coil, what is the effect on the current?

When the range of operating current for the coil and closed core just described extends over a sufficiently large amount, the flux-current graph is not a straight line. How then does one compute an appropriate self-inductance?

For alternating currents, where the current changes back and forth in direction, a straight line connecting a point on the graph corresponding to the maximum current is connected by a straight line through the origin to a similar point at the maximum negative current. The slope of this line is then the effective self-inductance.

The dashed line in Figure 8 is drawn for an alternating current with a maximum value of 1 ampere. The slope of this line is, from the graph, a "rise" of 0.135 Wb divided by a "run" of 1 A. The effective self-inductance is therefore 0.135 henry.

Problem 14

Using the graph of Figure 9, what is the effective self-inductance of this coil for an alternating current having a maximum value of 0.2 A?

We have seen that the flux produced by a coil with a closed iron core (in the shape of a ring) is proportional to the current only when the current is small. What happens when the core is not closed? The ignition coil core consists of a stack of flat iron strips, as shown in Figure 10, surrounded by an iron housing. An air gap exists between the iron core and the iron housing.

Where there is an air gap preventing a core from being closed, the magnetic effect on the domains in the core is greatly reduced, so that far less domains can contribute to the field than when there is no gap. As a result, the flux produced by an ignition coil is sufficiently small that the inductance is nearly constant over the range of operating currents. We may therefore use fixed values of self-inductance and mutual inductance for ignition coils.

Example Problem

A coil with a self-inductance of 6×10^{-2} henries has a current which changes from 1.5 A to zero in 0.05 seconds. What is the magnitude of the EMF induced in the coil?

Solution

Given are

$L = 6 \times 10^{-2}$ henry, $\Delta I = 1.5$ A and $\Delta t = 0.05$ seconds.

Substituting these values into equation (13) gives

$$E = -\frac{(6 \times 10^{-2}\ \text{henry})(1.5\ \text{A})}{5 \times 10^{-2}\ \text{seconds}},$$

$$E = -\frac{6 \times 1.5}{5}\ \frac{\text{henry-A}}{\text{second}}.$$

Performing the indicated arithmetic gives

$$E = -1.8\ \frac{\text{henry-A}}{\text{second}}.$$

Since 1 henry = 1 volt-second/A, our solution becomes

$$E = 1.8\ \frac{\left(\frac{\text{volt-second}}{\text{A}}\right)\text{A}}{\text{second}}$$

or

$$E = -1.8\ \text{volts}.$$

Problem 15

A coil with a self-inductance of 10 henries has a current which changes from 0.2 A to 0.1 A in 0.01 seconds. What is the magnitude of the EMF induced in the coil?

Example Problem

An automobile ignition coil has a mutual inductance of 0.5 henries. The current in the primary circuit changes from the maximum of 3 A to 1.5 A in 30 microseconds. What is the induced voltage in the secondary of the coil?

Solution

Given are

$M = 0.5$ henry, $\Delta I_1 = -1.5$ A, and $\Delta t = 3 \times 10^{-5}$ seconds.

Substituting these values into equation (14) gives

$$E_2 = -\frac{(0.5\ \text{henry})(-1.5\ \text{A})}{3 \times 10^{-5}\ \text{second}} .$$

Simplifying, we have

$$E_2 = \frac{0.5 \times 0.5}{10^{-5}} \ \frac{\text{henry-A}}{\text{second}}$$

or

$$E_2 = 0.25 \times 10^5 \ \frac{\text{henry-A}}{\text{second}} .$$

As shown in the previous example, $1 \ \frac{\text{henry-A}}{\text{second}} = 1$ volt.

Thus

$$E_2 = 25{,}000 \text{ volts.}$$

Problem 16

Calculate the induced EMF in the secondary of a coil with a mutual inductance of 0.06 henries, if the primary current increases by 2 A in 0.01 seconds.

Example Problem

How quickly must the current in the primary of a coil go from 5 amp to zero, if the average voltage induced in the secondary is 1000 volts and the coil has a mutual inductance of 0.2 henries?

Solution

Given are

$$M = 0.2 \text{ henry}, \ \Delta I_1 = -5 \text{ A and } E_2 = 1000 \text{ V}.$$

Equation (14) must be rearranged for Δt. Multiplying both sides of equation (14) by Δt and dividing by E_2 gives

$$\Delta t = -M \frac{\Delta I_1}{E_2} .$$

Substituting values into this equation gives

$$\Delta t = (-0.2 \text{ H})\left(\frac{-5 \text{ A}}{1000 \text{ volts}}\right).$$

Simplifying gives

$$\Delta t = 10^{-3} \ \frac{\text{henry-A}}{\text{volt}} .$$

Using the fact that 1 henry = 1 $\frac{\text{volt-second}}{\text{A}}$ we have

$$\Delta t = 10^{-3} \ \frac{\left(\frac{\text{volt-second}}{\text{A}}\right)\text{A}}{\text{volt}}$$

or

$$\Delta t = 10^{-3} \text{ seconds,}$$

which can be written

$$\Delta t = 1 \text{ ms.}$$

From this point on, the word second will be represented by the small letter, "s".

Problem 17

What time is required for the current in the primary of a coil to increase by 0.5 A? The mutual inductance is 0.01 henry, and an average EMF of -2 volts is induced in the secondary?

Question 10

The current in a coil is increasing at a certain rate, when another coil is brought close. If the latter coil has its ends connected together, so that it can carry a current, what happens to the current in the first coil?

A cross-section of the ignition coil is shown in Figure 10.

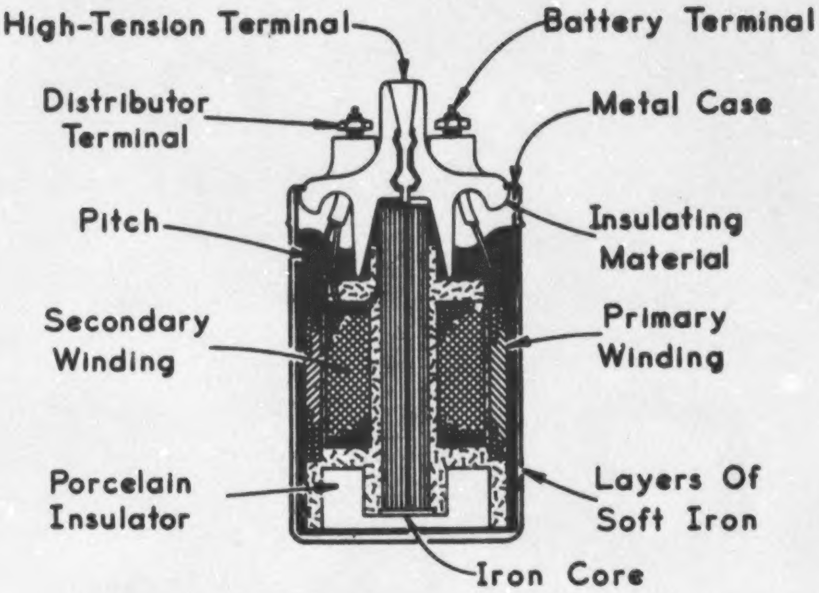

High-Tension Terminal
Battery Terminal
Distributor Terminal
Metal Case
Pitch
Insulating Material
Secondary Winding
Primary Winding
Porcelain Insulator
Layers Of Soft Iron
Iron Core

Figure 10

From this figure it can be seen that the primary and secondary coils are both wound around a soft iron core. This core concentrates the magnetic flux through the coils. The core is in thin strips, or laminated, in order to reduce the induced currents in the core itself. Since iron is a conductor, the changing flux of the primary coil would induce large currents in the core, with a subsequent electric power loss and excess heating of the whole assembly. These rather random induced currents in a large piece of metal are called eddy currents. Because it is difficult for the current to cross the boundaries between strips, the laminated design acts to decrease eddy currents.

Figure 10 also shows the relatively large number of turns in the secondary compared to the small number in the primary. The primary coil winding is made up of a few hundred (150-250) turns of No. 20 Gauge wire, which is about the size used in making ordinary paper clips. The secondary coil winding consists of many thousands of turns (15000-25000) of No. 40 gauge wire, which is about as fine as human hair. According to equation (11), the many turns of the secondary coil cause a very large induced voltage in the secondary circuit for a given rate of change of the flux.

Figure 11 summarizes the function of the ignition coil by diagramming the operation of the primary and secondary circuits.

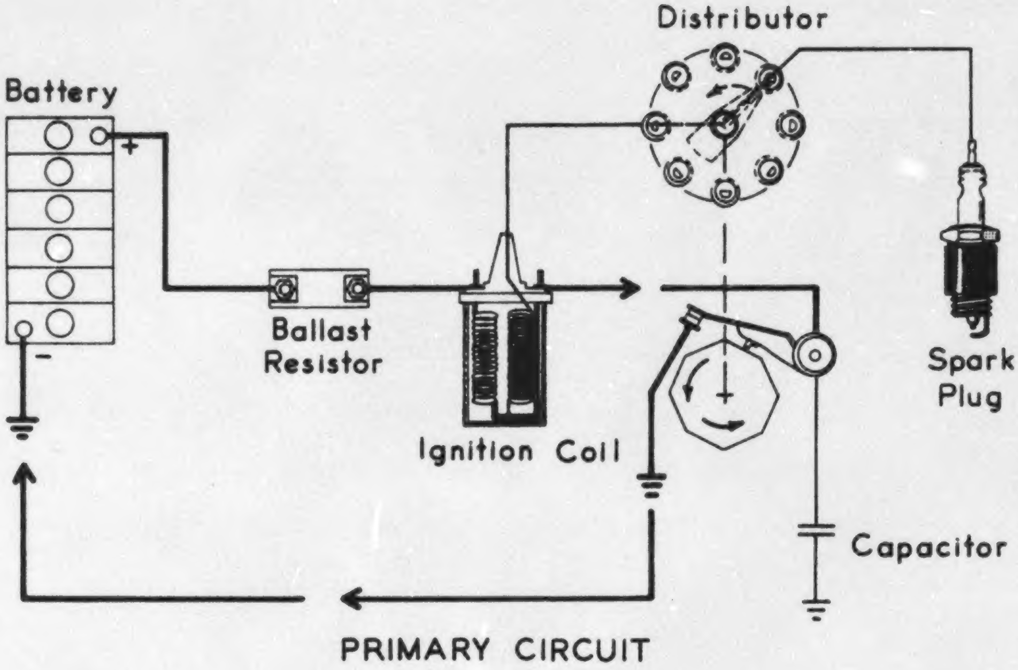

Distributor
Battery
+
−
Ballast Resistor
Ignition Coil
Spark Plug
Capacitor
PRIMARY CIRCUIT

Figure 11a

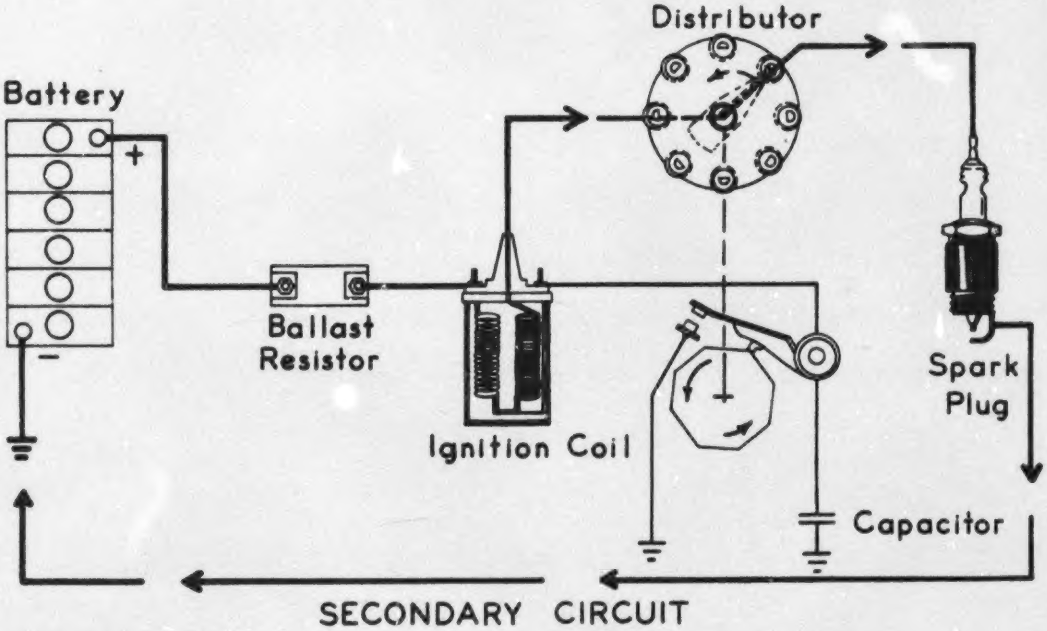

Distributor
Battery
+
−
Ballast Resistor
Ignition Coil
Spark Plug
Capacitor
SECONDARY CIRCUIT

Figure 11b

Figure 11a shows the primary circuit, which is completed only when the points are closed. The 12 volt battery supplies a current which reaches a maximum of about 3 amps through the primary of the coil, since the resistance of the primary circuit is about 4 ohms. This current is the source of the magnetic field in the induction coil. Notice that the circuit is completed through the metal parts of the engine which act as a common "ground". Referring to figure 11b we see that once the points have opened, the magnetic field which was built up in the coil by the current in the primary circuit now collapses, since the current is reduced to zero rapidly. This collapsing field then induces the high voltage for the spark which occurs in the rotor cap and spark plug in the secondary circuit. Note that the battery is also part of the secondary circuit. The current in the secondary is so small however, that it has little effect on the battery. As in the primary circuit the engine provides the "ground" which completes the circuit in the secondary.

IV. CAPACITANCE

An important feature of the distributor is the capacitor which is connected across the breaker points. This capacitor prevents sparking across the points as they open. Such an electric arc would cause excessive wear of the points, and it would also reduce the rate of change of the primary current, thereby reducing the induced EMF in the secondary.

Any pair of conductors placed near each other form a capacitor. They are said to have capacitance, which is a measure of the ability to store charge. Suppose that electric charge is transferred between two conductors, so that one conductor acquires a positive charge Q and the other an equal negative charge -Q. This charging of the conductors will result in a potential difference between them, with the positive conductor having a higher potential. The potential difference V will be proportional to the amount of the charge Q. The constant of proportionality, called capacitance C, is defined so that

$$\boxed{C = Q/V.} \quad \text{(definition of electric capacitance)} \quad (15)$$

Units of capacitance are called farads (1 farad = 1 coulomb/volt) after Michael Faraday. The capacitance of a pair of conductors depends only on their geometry, orientation, and on the medium which separates them. Actually one farad is an extremely large unit of capacitance, and units of microfarads or picofarads are more commonly used. The capacitor in an ignition system is simply two long strips of metal foil with a strip of insulating material between them. The resulting sandwich is rolled up and put into a little can.

Example Problem

Determine the capacitance of a capacitor which has a charge of 5×10^{-2} coulomb, when the potential difference across it is 500 volts.

Solution

Given are

$$Q = 5 \times 10^{-2} \text{ coulomb, and } V = 500 \text{ volts.}$$

Substituting these values into equation (15) gives

$$C = \frac{5 \times 10^{-2} \text{ coulomb}}{5 \times 10^{2} \text{ volts}} .$$

Simplifying this gives

$$C = 1 \times 10^{-4} \text{ coulomb/volt.}$$

Since 1 farad = 1 coulomb/volt, the solution may be written as

$$C = 1 \times 10^{2} \times 10^{-6} \text{ farad.}$$

Recalling that 10^{-6} farad = 1 microfarad,

$$C = 100 \text{ microfarad}$$

for our solution.

Problem 18

What is the capacitance of a capacitor that has a charge of 6×10^{-3} coulomb, when the potential difference across it is 150 volts?

Example Problem

The capacitor across the points of a particular automobile has a capacitance of 0.1 microfarad. If the primary voltage is 12 volts, what amount of charge is stored in this capacitor?

Solution

Given are

$$C = 0.1 \text{ microfarad} = 0.1 \times 10^{-6} \text{ farad, and } V = 12 \text{ volts.}$$

Rearranging equation (15) gives

$$Q = CV.$$

Substituting values into this equation we have

$$Q = (0.1 \times 10^{-6} \text{ farad}) (12 \text{ volts})$$

or

$$Q = 1.2 \times 10^{-6} \text{ farad-volts.}$$

Substituting for farad we get

$$Q = 1.2 \times 10^{-6} \left(\frac{\text{coulomb}}{\text{volt}}\right) (\text{volt})$$

or

$$Q = 1.2 \times 10^{-6} \text{ coulomb.}$$

From this point on, the word coulomb will be represented by the letter "C", and word farad will be represented by the letter "F".

Problem 19

The starting capacitor on an electric motor is 400 μF. If the maximum potential across it is 220 volts, what is the maximum charge stored in the capacitor?

Question 11

From what you know about electric forces, would it be easier or harder to place opposite charges on two parallel plates when they are close together than further apart? What does this mean in terms of capacitance?

The capacitor which is attached across the points in an ignition system, allows the current in the primary circuit to continue flowing for a fraction of a second after the points break contact.

If the capacitor were not present, it would be difficult to interrupt the current in the primary circuit by opening the points. An inductance resists changes in current. Any current change causes a voltage which tends to maintain the prior state of current. Therefore, when the points open the current does not immediately stop. The rapid decrease in current induces a voltage in the coil which is large enough to produce arcing across the points. By arcing, the current is maintained.

But arcing at the points severly reduces the life of the points. Furthermore, the voltage at the spark plug is reduced. Consequently, a capacitor (condensor) is placed across the points. Then when the points are opened, the current can momentarily be diverted into the capacitor, and this effect minimizes the arcing at the points. By the time the capacitor is fully charged, the points have opened too far for a spark to jump the gap, and the primary current then decreases very rapidly.

V. TRANSIENT CURRENTS

The current in an ignition system is changing rapidly with time. It is not direct current because it is not steady. It is not alternating current such as the current in household circuits, because it does not alternate uniformly between a positive value and a negative value. Currents in ignition systems are quite complicated and they fall in category of *transient currents*.

One problem with a conventional ignition system is the loss of full primary current at high engine speeds. At high speeds, the points are not closed long enough for the primary current to build up to its full value. That value would be the battery voltage divided by the primary resistance (a few ohms). If the primary current is smaller at high speeds than at low speeds, the induced EMF in the secondary will be smaller at high speeds.

The function of the ballast resistor depends upon the relationship of resistance to temperature. This resistor tends to balance the effects of engine speed on the ignition coil circuit. When the engine is running rapidly, the points are closed only a very short time, so that the primary current does not have time to build up to the full value it attains at lower speeds. Due to the primary current itself, the ballast resistor heats up at low speeds, and the increased resistance limits the current. At higher engine speeds, the current, flowing for a shorter time, does not heat up the resistor as much, so that its resistance lowers, and more current can flow. The ballast resistor, therefore, causes a more uniform spark voltage at all engine speeds.

When the points of an ignition system close, the current does not reach its maximum value immediately. Instead, it builds up as shown in Figure 12.

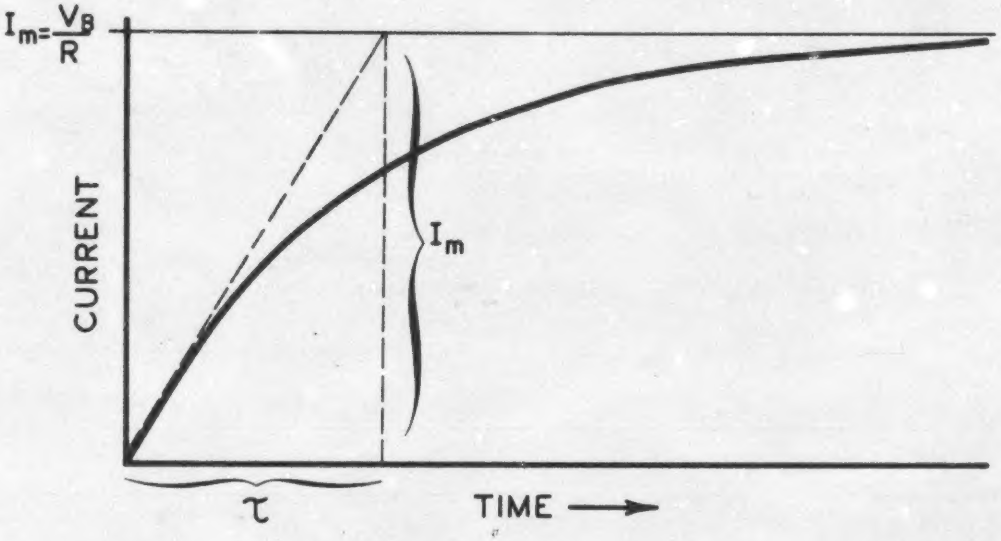


Figure 12

The gradual current buildup is due to the inductance of the primary coil, which will produce an EMF opposing the increasing current. With the points closed, the capacitor is "shorted", and the primary circuit is essentially as diagrammed in Figure 13.

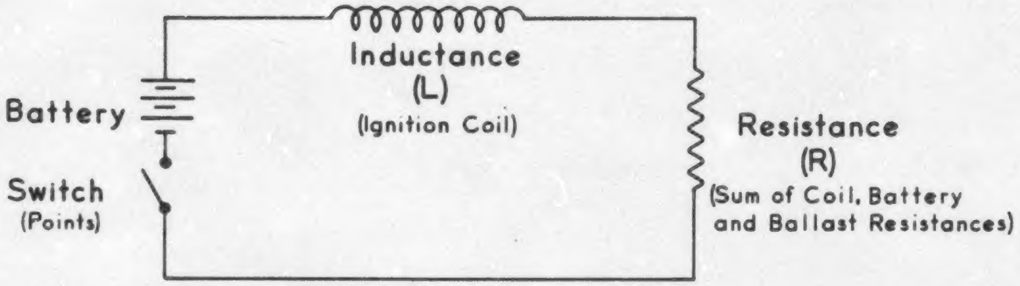

Inductance
(L)
(Ignition Coil)
Battery
Switch
(Points)
Resistance
(R)
(Sum of Coil, Battery and Ballast Resistances)

Figure 13

In this figure, the resistance R includes the ballast resistor, the resistance of the primary coil, and the internal resistance of the battery. The circuit shown is called an L-R circuit. If the circuit has just been closed the current will build up from zero and approach a constant value. The constant value will be V_B/R, where V_B is the voltage of the battery and R is the total resistance of the circuit.

In a series L-R circuit, the applied voltage is equal to the sum of the voltage drops across the inductance and the resistance. If we sum the resistances of an ignition coil primary circuit, we have

$$R_p + R_B + R_I = R,$$

where R_p is the primary coil resistance, R_B is the ballast resistance, R_I is the internal resistance of the battery, and R is the total resistance in the primary circuit. Typical values of these quantities are

$$R_p = 1.47\ \Omega,$$

$$R_B = 1.95\ \Omega, \text{ and}$$

$$R_I = 0.03\ \Omega,$$

for a total of

$$R = 3.45\ \Omega.$$

The voltage drop across the primary circuit resistance is then $I_pR_p + I_pR_B + I_pR_I$, or more simple I_pR, where I_p is the primary current.

The voltage drop across the primary inductance, is, from Equation (13), $L_p\left(\frac{\Delta I_p}{\Delta t}\right)$, where L_p is the value of the primary coil inductance. If the battery terminal voltage (the zero-current value of voltage) is V_B, our statement about the voltage drops across the circuit elements can be written as

$$V_B = L_p\left(\frac{\Delta I_p}{\Delta t}\right) + I_p R. \qquad (16)$$

If this equation is solved for L_p, we have

$$L_p = \frac{V_B - I_pR}{(\Delta I_p/\Delta t)}\,. \qquad (17)$$

The denominator of this equation is the slope (at a certain time) of the graph of Figure 13, which shows current versus time. When the inductance is constant, the quantity $V_B - I_p R$ divided by the slope taken at any time will give the inductance. At a particular time, t, the inductance can therefore be found from the equation:

$$L_p = \frac{V_B - I_p R}{\text{(slope of I-t curve at time t)}} . \qquad (18)$$

At the time, t=0, where $I_p = 0$, and therefore, $I_p R = 0$, the inductance can be found from the simpler equation

$$\boxed{L_p = \frac{V_B}{\text{(slope of I-t curve at t = 0)}}} \qquad \text{(Inductance from the slope of a graph of I versus t).} \quad (19)$$

To apply equation (19) to the graph of Figure 13, a line is drawn tangent to the curve at t = 0 (the origin) and extended until it meets the horizontal line of maximum current, I_m. Then the slope of this tangent line is the rise, I_m, divided by the "run", τ. If we write Equation (19) in terms of these quantities, we have

$$L_p = \frac{V_B}{I_m/\tau},$$

or

$$L_p = \tau \ (V_B/I_m).$$

Now, the terminal voltage, V_B, divided by the maximum current, I_m is, from Ohm's law, just the total resistance of the circuit, R. Thus we have

$$L_p = \tau R,$$

or

$$\boxed{\tau = L_p/R.} \quad \text{(Time constant of an L-R circuit)} \qquad (20)$$

This time, τ, is an important characteristic of an L-R circuit. It is called the *time constant* because for any L-R circuit, the current builds to the same fraction (63.2%) of its maximum value in this time.

Example Problem

If the primary inductance of an ignition coil is 7×10^{-3} henry and the resistance in the primary circuit is 4 Ω in a 12 volt system, what is the maximum value of current in the primary and what is the time constant for the circuit?

Solution

Given are

$$L = 7 \times 10^{-3} \text{ henry}, V = 12 \text{ volts, and } R = 4\ \Omega.$$

For the maximum current, from Figure 13,

$$I_m = V_B/R.$$

Substituting values into this equation gives

$$I_m = 12 \text{ volt}/4\ \Omega$$

or

$$I_m = 3 \text{ volt}/\Omega.$$

Since 1 Ω = 1 volt/A

$$I_m = 3 \text{ A}.$$

In order to find the time constant, values are substituted into Equation (20), so that

$$\tau = \frac{7 \times 10^{-3} \text{ henry}}{4\ \Omega}$$

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Simplifying this gives

$$\tau = 1.2 \times 10^{-3} \frac{\text{henry}}{\Omega} .$$

Since 1 henry = 1 Ω-s,

$$\tau = 1.2 \times 10^{-3} \frac{\Omega\text{-s}}{\Omega}$$

or

$$\tau = 1.2 \text{ milliseconds,}$$

and the current builds to 63.2% of its maximum value in this time. From this point on, the unit word henry will be represented by the letter "H".

Problem 20

If the inductance of a coil is 2×10^{-2} H and the circuit containing the inductance has a resistance of 0.5 Ω, what is the time constant for this circuit?

Question 12

A coil of wire has a certain inductance, resistance, and time constant. What happens to the time constant when the temperature of the wire is increased? For resistivities of the order of $10^{-3}/^{\circ}$ C, what order of change in the time constant is expected for typical temperature changes?

If the battery were absent in this circuit and there was an initial current, the opposite effect would take place. The inductance would tend to keep the current from decreasing, although the energy of the moving charges is lost in the resistance. Thus, the current would gradually approach zero as shown in Figure 14.

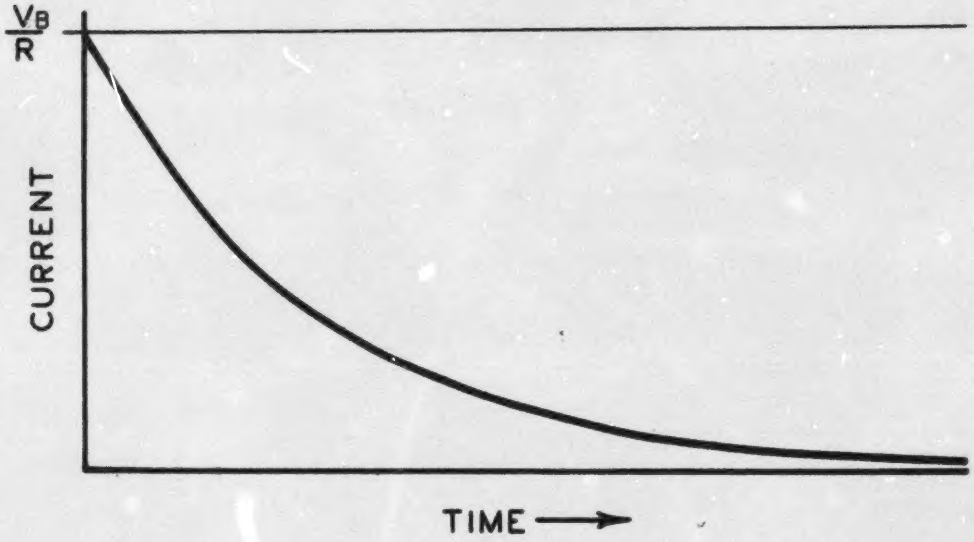

Figure 14

In this case, the inductance is given by,

$$L = \frac{I_p R}{(\text{slope of I-t curve at time t})} \,. \tag{21}$$

At t = 0, $I_p R$ is just V_B, and since the slope is $-I_m/\tau$, the value of the time constant is, L_p/R, the same as we had for the case of increasing current in that L-R circuit.

Example Problem

If the graph of current versus time in a circuit which contains an inductor and total resistance of 5 Ω has an initial slope of -3,000 A/s and a maximum current of

3 A, what is the inductance for this circuit? What is the time constant?

Solution

Given are

$$R = 5\ \Omega,\ I_m = 3\ \text{A, and slope} = -3{,}000\ \text{A/s}.$$

Using equation (21) at t = 0,

$$L = \frac{-I_m R}{(\text{slope of I-t curve at } t = 0)} .$$

Substituting values into this equation, we have

$$L = \frac{(-3)(5)\ \Omega\text{-A}}{-3000\ \text{A/s}} = 5 \times 10^{-3}\ \Omega\text{-s},$$

or

$$L = 5 \times 10^{-3}\ \text{H}.$$

The time constant is given by L/R, or

$$\tau = \frac{5 \times 10^{-3}\ \Omega\text{-s}}{5\ \Omega} = 10^{-3}\ \text{s} = 1\ \text{ms}.$$

Problem 21

The current in an L-R circuit decreases from a maximum of 6 A to zero as shown in Figure 14. If the initial slope is -2000 A/s and the resistance of the circuit is 0.10 Ω, what is the inductance? What is the time constant?

When the points are open, the primary circuit consists of a resistance, an inductance, and a capacitance in series with the battery. It is informative to consider first the case of just an inductance and a capacitance in series. Such a situation, known as an L-C circuit, will more clearly show the role of the capacitance. This circuit is shown in Figure 15.

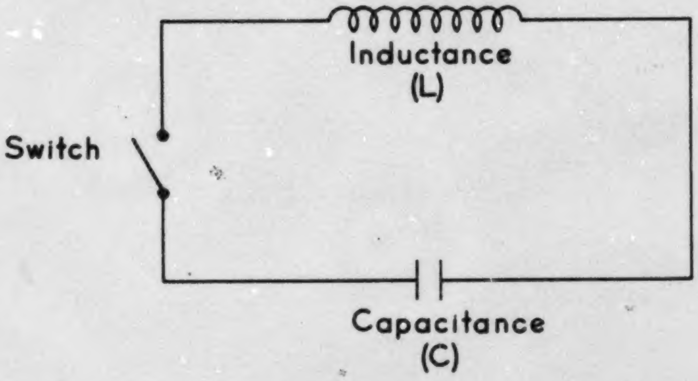
Inductance
(L)
Switch
Capacitance
(C)

Figure 15

This circuit is similar to the primary circuit with the points opened and the battery and resistance missing.

Suppose the capacitor has been fully charged before being placed in this circuit. When the switch is closed, there is an oscillation of current as shown in Figure 16.

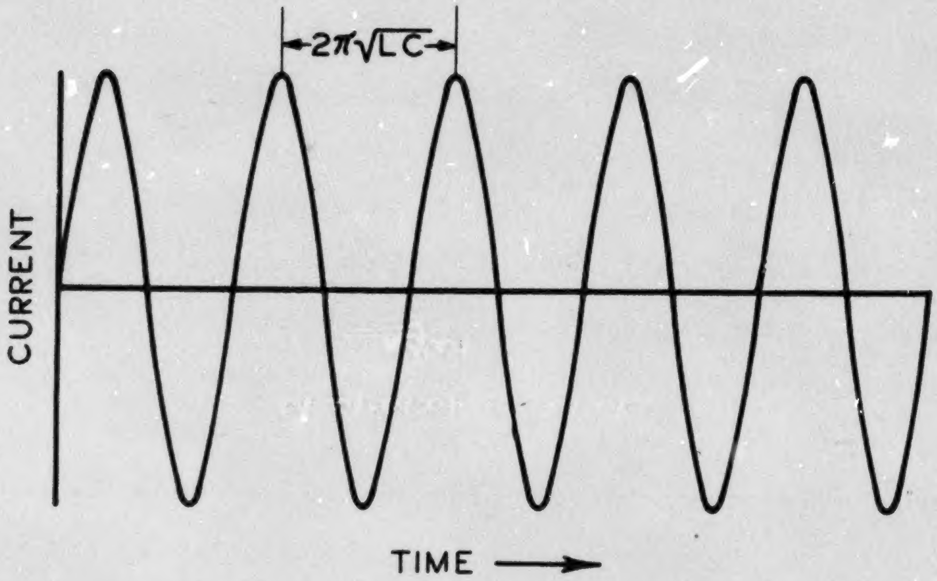

Figure 16

This oscillation can be explained as follows: The capacitor starts to discharge through the inductance, and the current builds up rapidly from zero. This increasing current induces an EMF in the coil, which opposes the current. The induced EMF and the discharge of the capacitor slow down the rate of increase of the current, which in turn reduces the induced EMF. Although the current continues to increase until the capacitor is fully discharged, its rate of increase is less and less. When the charge stored on the capacitor is zero, the current is no longer increasing (it has reached a maximum), and the induced EMF is also zero. From this point on, the current starts to charge the capacitor in the opposite direction, which causes the current to decrease. Now the decreasing current produces an EMF in the coil which tends to keep it going until the capacitor is fully charged in the opposite direction. The whole process repeats itself with current flowing in the reverse direction. The net result is that the current keeps changing direction, charging the capacitor first one way and then the other. From observations of such circuits, we know that a graph of current versus time is as shown in Figure 16. A counterclockwise current in the circuit of Figure 15 is taken as positive.

This circuit is called an oscillating circuit. The period of oscillation, T, is defined as the time for one complete oscillation, which is the time from the beginning of the process until the capacitor is fully charged in the same direction again.

The following derivation is optional. You may go ahead to equation (27) if you do not care to understand its derivation.

Since the graph of Figure 16 is that of the function,

$$I = I_m \sin (2\pi\ t/T), \tag{22}$$

the quantity $T/2\pi$ must depend on the capacitance and inductance in some way. Because the current has the form of the graph in Figure 16, the charge on the capacitor must have the shape of a cosine graph. When the current is maximum, the charge is zero; similarly, when the current is zero, the charge is maximum. We can therefore write the charge equation as

$$Q = -Q_m \cos(2\pi\ t/T). \tag{23}$$

Now, let us find the maximum current by finding the slope of the graph of equation (23) when it first has its greatest value. This slope occurs at a time of T/4, where

$$Q = -Q_m \cos(\pi/2) = 0.$$

At a time Δt earlier, where $t = T/4 - \Delta t$,

$$Q = -Q_m \cos(\pi/2 - 2\pi\Delta t/T).$$

Now, recalling from trigonometry that

$$\cos(\pi/2-\theta) = \sin\theta,$$

we have

$$Q = -Q_m \sin(2\pi\Delta t/T).$$

But for very small values of Δt, the angle $2\pi\Delta t/T$ is also very small. For small angles, the sine of an angle is equal to the angle; therefore, we have

$$Q = -Q_m\, 2\pi\Delta t/T.$$

The charge has changed by an amount

$$\Delta Q = 0 - (-Q_m\, 2\pi\Delta t/T) = +(2\pi\Delta t/T)\,Q_m.$$

The maximum current, I_m, is therefore, $\Delta Q/\Delta t$, or

$$I_m = +(2\pi/T)Q_m,$$

and we can write equation (22) as

$$I = (2\pi/T)Q_m \sin(2\pi\, t/T). \qquad (24)$$

Let us now consider the sum of the voltages dropped across the components of an L-C circuit. Across the inductance we have $L(\Delta I/\Delta t)$. Across the capacitor, since $Q = CV$, we have a drop of Q/C. If the applied voltage in the circuit is zero, the sum of these voltages is zero, and we have

$$L(\Delta I/\Delta t) + Q/C = 0. \qquad (25)$$

Now, we have I versus t in equation (24). Let us find its slope $\Delta I/\Delta t$ at time, $t = 0$, where $Q = -Q_m$. Then

$$L \text{ x(slope of I-t curve at } t = 0) + -Q_m/C = 0. \qquad (26)$$

To find the slope at $t = 0$, we must find I at $t = 0$ and again at $t = \Delta t$. Then the difference, ΔI, can be divided by Δt to get the slope. We have at $t = 0$

$$I_o = (2\pi/T)Q_m \sin(0) = 0,$$

and at time $t = \Delta t$,

$$I_{\Delta t} = (2\pi/T)Q_m \sin(2\pi\Delta t/T).$$

Again, since Δt is very small, the sine of the angle can be taken equal to the angle, and we have

$$I_{\Delta t} = 2\pi/T\ Q_m\ (2\pi\Delta t/T).$$

The difference, ΔI, is therefore

$$\Delta I = (2\pi/T)^2\ Q_m\ \Delta t$$

and the slope $\Delta I/\Delta t$ is

$$\text{slope} = (2\pi/T)^2\ Q_m.$$

Using this slope in equation (26), we have

$$L(2\pi/T)^2 Q_m + -Q_m/C = 0$$

or dividing out the common factor Q_m, and multiplying both sides of the equation by C,

$$LC(2\pi/T)^2 - 1 = 0$$

adding 1 to both sides, we have

$$LC(2\pi/T)^2 = 1.$$

Multiplying both members by $(T/2\pi)^2$, we get

$$(T/2\pi)^2 = LC.$$

Taking the square root of both members,

$$T/2\pi = \sqrt{LC}$$

so that

$$\boxed{T = 2\pi\sqrt{LC}} \quad \text{(Period of Oscillation of L-C circuit)} \qquad (27)$$

We have, therefore determined the period, T, of oscillation of an L-C circuit in terms of the valuesof the inductance and capacitance. We often also speak of the frequency of oscillation, f, which is the number of oscillations per second. If T is the number of seconds per oscillation and f is the number of oscillations per second, we must have

$$f = 1/T = (1/2\pi)\sqrt{1/LC}\ . \qquad (28)$$

Frequency has dimensions of 1/s, called a Hertz.

Example Problem

What is the period of oscillation for an L-C circuit in which there is an inductance of 2.0 H and a capacitance of 4.5 μF?

Solution

Given are

$$L = 2.0 \text{ H and } C = 4.5 \times 10^{-6} \text{ F}.$$

Substituting these values into equation (27), we have

$$T = (2)(3.14)\sqrt{2 \times 4.5 \times 10^{-6} \text{ H-F}} .$$

Simplifying gives

$$T = (6.28)(3 \times 10^{-3})\sqrt{\text{H-F}}.$$

The result then is

$$T = 18.8\sqrt{\text{H-F}} .$$

In order to show that $\sqrt{\text{H-F}}$ has units of time, it is necessary to recall some earlier unit definitions,

$$1 \text{ F} = 1 \text{ C/volt and } 1 \text{ H} = 1 \text{ volt-s/A}.$$

We also had 1 A = 1 C/s.

Substituting these values into $\sqrt{\text{H-F}}$, we have

$$\sqrt{\text{H-F}} = \sqrt{\frac{\text{volt-s}}{\text{C/s}} \times \frac{\text{C}}{\text{volt}}}$$

or

$$\sqrt{\text{H-F}} = \sqrt{\text{s}^2} = \text{s}.$$

Thus our solution for the period of oscillation is

$$T = 18.8 \text{ s}.$$

Problem 22

If it had no resistance, what would be the period of oscillation for the primary circuit of an automobile ignition system? The inductance is 7×10^{-3} H, and the capacitance is 0.1 μF.

Question 13

Suppose an L-C circuit has a fixed capacitor and an air-coil inductor. What happens to the frequency of oscillation, when a soft iron core is inserted in the coil?

Example Problem

Determine the frequency of oscillation for an L-C circuit in which the inductance is 5×10^{-2} H and the capacitance is 5 pF.

Solution

Given are

$$L = 5 \times 10^{-2} \text{ H and } C = 5 \times 10^{-12} \text{ F}.$$

Substituting into equation (28)

$$f = \frac{1}{6.28} \times \frac{1}{\sqrt{5 \times 10^{-2} \text{ H} \times 5 \times 10^{-12} \text{ F}}}.$$

Simplifying gives

$$f = \frac{1}{6.28} \times \frac{1}{\sqrt{25 \times 10^{-14} \text{ H-F}}}.$$

Taking the square root gives

$$f = \frac{1}{6.28} \times \frac{1}{5} \times \frac{1}{10^{-7}} \times \frac{1}{\sqrt{H\text{-}F}} .$$

Simplifying this gives

$$f = 0.032 \times 10^{7} \times 1/\sqrt{H\text{-}F}$$

Since $\sqrt{H\text{-}F} = s$,

$$f = 3.2 \times 10^{5} \ 1/s.$$

But 1 Hz = 1/s, thus

$$f = 3.2 \times 10^{5} \text{ Hz}.$$

Problem 23

Determine the frequency of oscillation for an L-C circuit in which the inductance is 1.2×10^{-2} H and the capacitance is 0.3 μF.

The actual primary circuit, of an ignition system, when the points just open, is an L-C-R circuit in principle like the one shown in Figure (17).

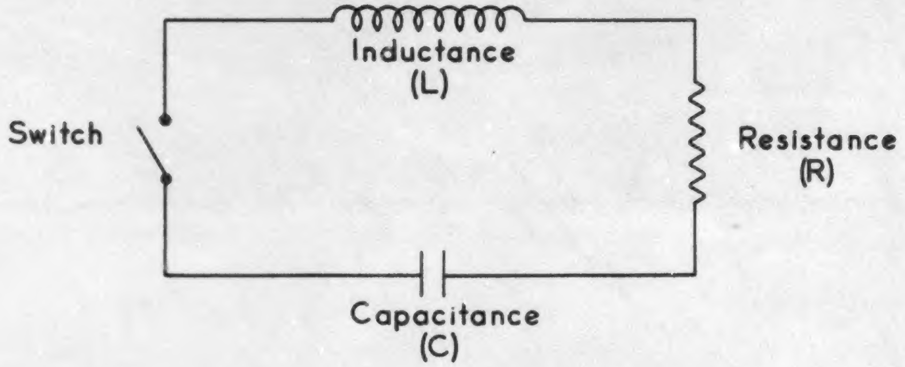
Inductance
(L)
Switch
Resistance
(R)
Capacitance
(C)

Figure 17

In this circuit we get a combination of the effects studied earlier. The capacitance and inductance give rise to an oscillating current, and the resistance, which dissipates energy, causes a decay of the oscillating current. The combined effect is called a damped oscillation and is shown in Figure (18).

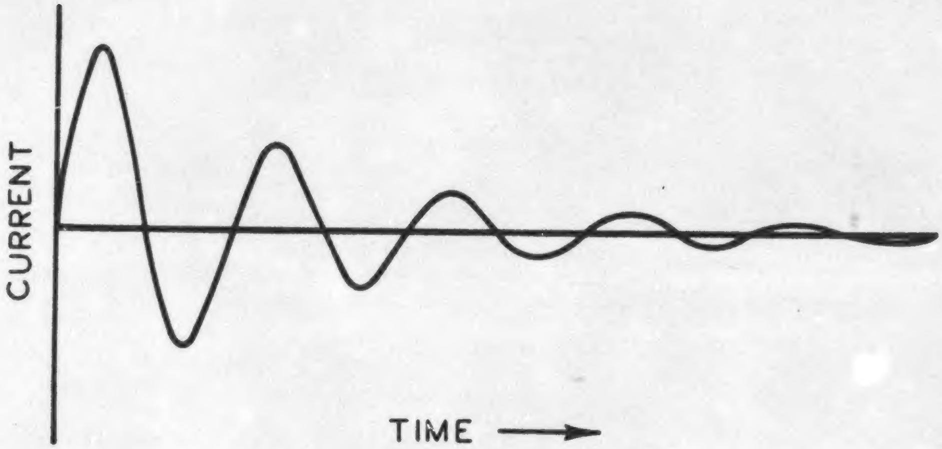

Figure 18

Even this rather complicated picture of the situation is not sufficient to explain the transient currents in the primary circuit of an ignition system in full detail. We have left out the interaction between the primary and secondary circuits through the mutual inductance of the coils. This interaction is significant and complex, as you can now see by performing *Experiment 5: An Analysis of the Ignition System.*

EXPERIMENT 5

AN ANALYSIS OF THE IGNITION SYSTEM

The primary function of the ignition system of an automobile is to convert low-voltage direct current from a battery into high voltage pulses which are distributed to each spark plug.

A typical ignition system is shown in Figure 4 of the text. Only the essential features are illustrated.

The ignition system is divided into two circuits, a primary (low-voltage) and a secondary (high-voltage) circuit. The primary circuit consists of the battery, ballast resistor, primary winding of the ignition coil, capacitor, and breaker points. The secondary circuit consists of the secondary winding of the ignition coil, distributor and spark plugs.

A convenient way of observing ignition system performance is by means of the basic waveform displayed on an oscilloscope.

The ignition system waveform, as developed across the *ballast resistance* R_B, is shown in Figure 1. For purposes of analyzing the oscilloscope waveform, it is divided into three sections: the dwell section; the firing section; and the intermediate section. These sections are labeled in Figure 1.

The Dwell Section

This section of the waveform represents the period of time during which the breaker points are closed. At time A, the points close, and the current in the primary builds up to a maximum at time B, producing a maximum magnetic field in the primary windings. The growth rate of the current is determined by the time constant

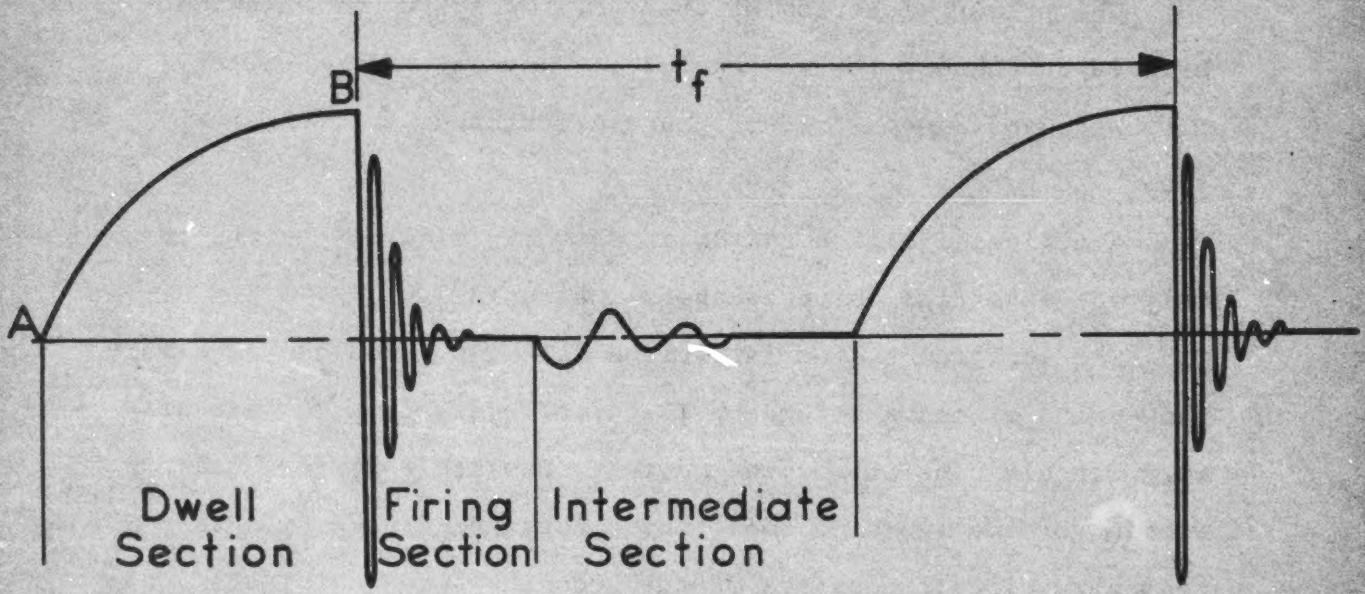

Figure 1

of the circuit (given by $\tau = L_p/R$). The inductance, L_p, is the inductance of the primary winding of the ignition coil, and R is the total resistance in the primary circuit. The total resistance R is the sum of the ballast resistance R_B and the resistance of the primary winding R_p.

Let us now determine the time constant τ of the circuit, and from the time constant evaluate the inductance, L_p, of the primary circuit (using equation $L_p = \tau R$).

The total resistance R can be found by measuring the ballast resistance R_B and the primary resistance R_p by means of an ohm-meter or Wheatstone bridge.

Connect the oscilloscope across the ballast resistance R_B. Make the appropriate adjustments of the oscilloscope controls to obtain a waveform similar to the one shown in Figure 1.

The time constant, τ, is the time for the current (and likewise the voltage) to reach 63.2% of its maximum value. This interpretation is shown in Figure 2.

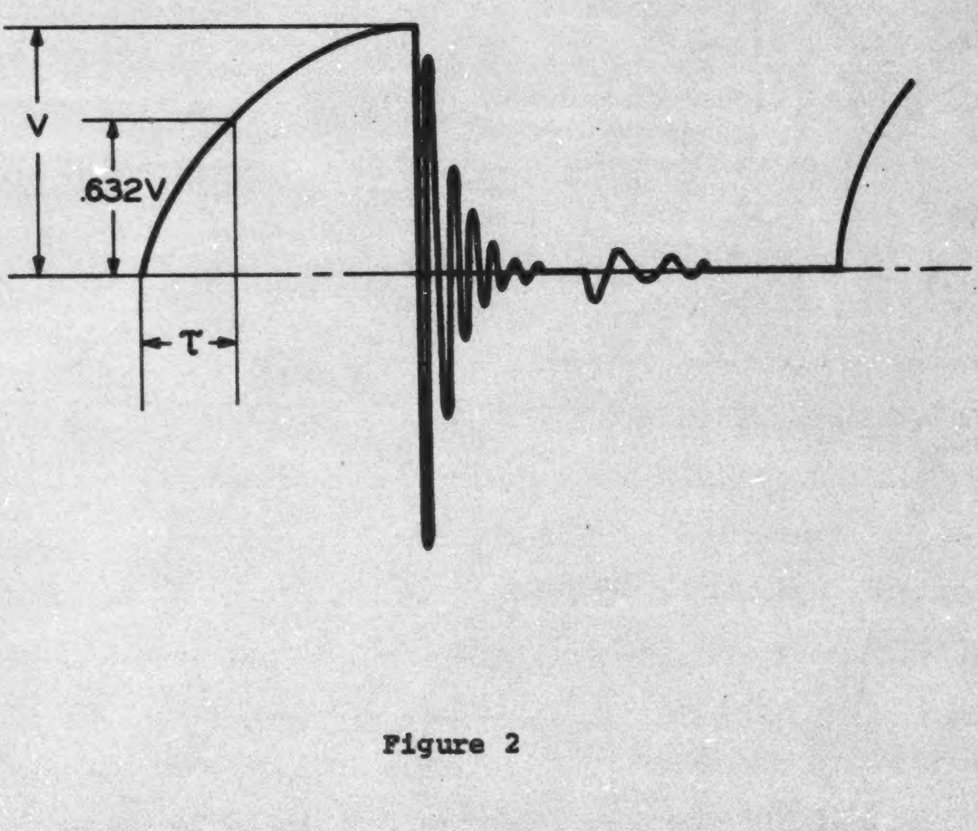

Figure 2

Measure the time constant τ, and determine the inductance of the primary from

$$L_p = \tau R$$

where τ is in seconds, R is in ohms, and L_p is in henries.

The time t_D over the interval A to B as shown in Figure 1 is the time the breaker points are closed, and is referred to as the *dwell time*. The *dwell* is usually expressed in terms of the number of degrees through which the distributor cam turns during the time the points are closed. For a cam having eight lobes, the angle between each lobe is $360^\circ/8$, or 45°. The cam therefore rotates through an angle of 45° between the firing of one spark plug to the next. It rotates 45° in the time interval t_f between firing of spark plugs. The time interval t_f is shown in Figure 1.

The *dwell*, in degrees, is the ratio of time the points are closed, t_D, to the total time between firing of the spark plugs t_f, times the angle 45°. This relationship is expressed by the equation,

$$\text{dwell} = \frac{t_D}{t_f} \times 45^\circ.$$

From the waveform, determine the time intervals t_D and t_f, and evaluate the dwell.

A distributor which has operated for a considerable number of miles, becomes worn, causing the dwell to change. In all distributors, a means is provided to adjust the point gap, which increases or decreases the dwell. The adjustment usually includes turning a screw attached to the breaker point assembly. The optimum dwell is in the range of 28 to 32°. If the above measured dwell is not within this range of angles, make the adjustment.

The Firing Section

This section can best be analyzed by looking at the waveform across the primary winding of the ignition coil. A typical waveform across a primary winding is shown in Figure 3.

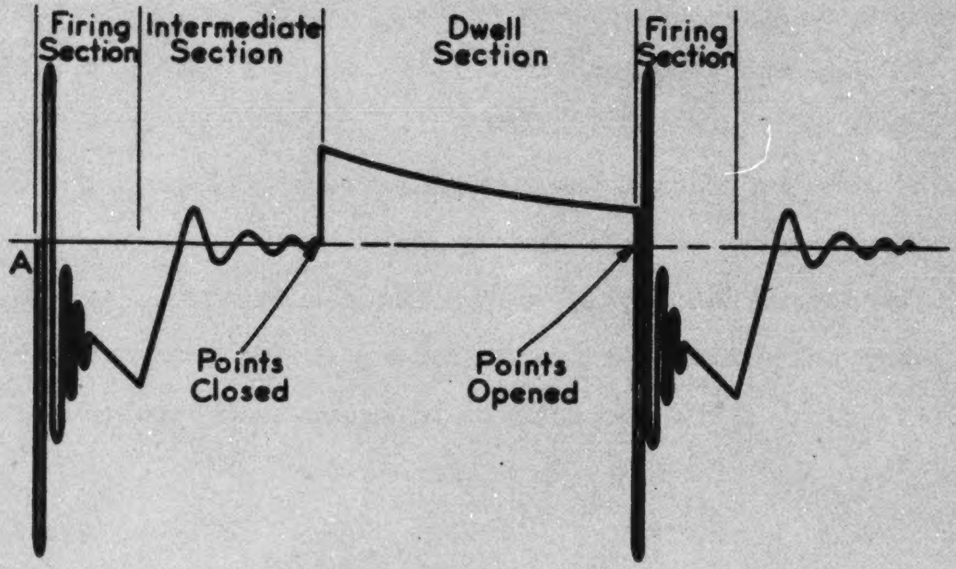
Firing Section
Intermediate Section
Dwell Section
Firing Section
A
Points Closed
Points Opened

Figure 3

The firing section is so called, because it is during this interval that the actual firing of the spark plug takes place.

When the points open, the current decreases abruptly, collapsing the magnetic field linking the primary and secondary windings. The rapidly changing magnetic field through the many thousands of turns in the secondary generate a voltage of about 25,000 to 30,000 volts which is applied through the distributor cap to the spark plugs.

The rapid oscillation of the firing in the secondary is seen in the primary circuit because these two circuits are linked magnetically. These oscillations begin at the point A when the points open. The plug-firing oscillations diminish after the plug begins to fire, since less voltage is needed to sustain a spark across the plug gap, once it is started. The firing oscillations continue to diminish until the voltage shown by the spark line is reached and the plug stops firing.

The period, T_S, of the firing oscillation of the secondary circuit is determined mainly by the inductance of the secondary winding and the distributed capacitance between the very large number of turns in the secondary. An equivalent circuit for the secondary circuit is shown in Figure 4.

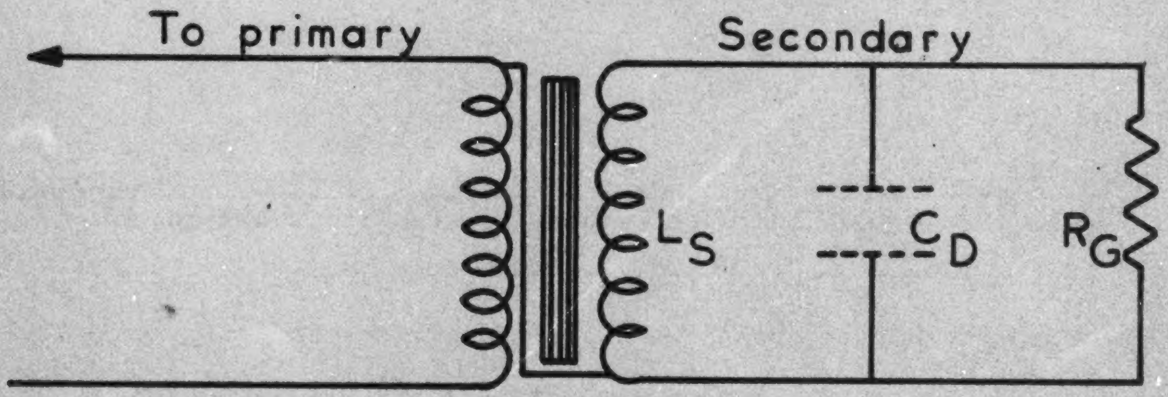

Figure 4

The capacitance between the windings is shown as C_D. The resistance, R_G, represents the sum of the large resistance of the spark gap and the resistance of the secondary winding. This resistance causes the rapid drain of energy from the secondary circuit during the firing of the spark plug.

To analyze the secondary oscillation, we need to expand the pattern by an adjustment of the time base to obtain a pattern similar to that shown in Figure 5.

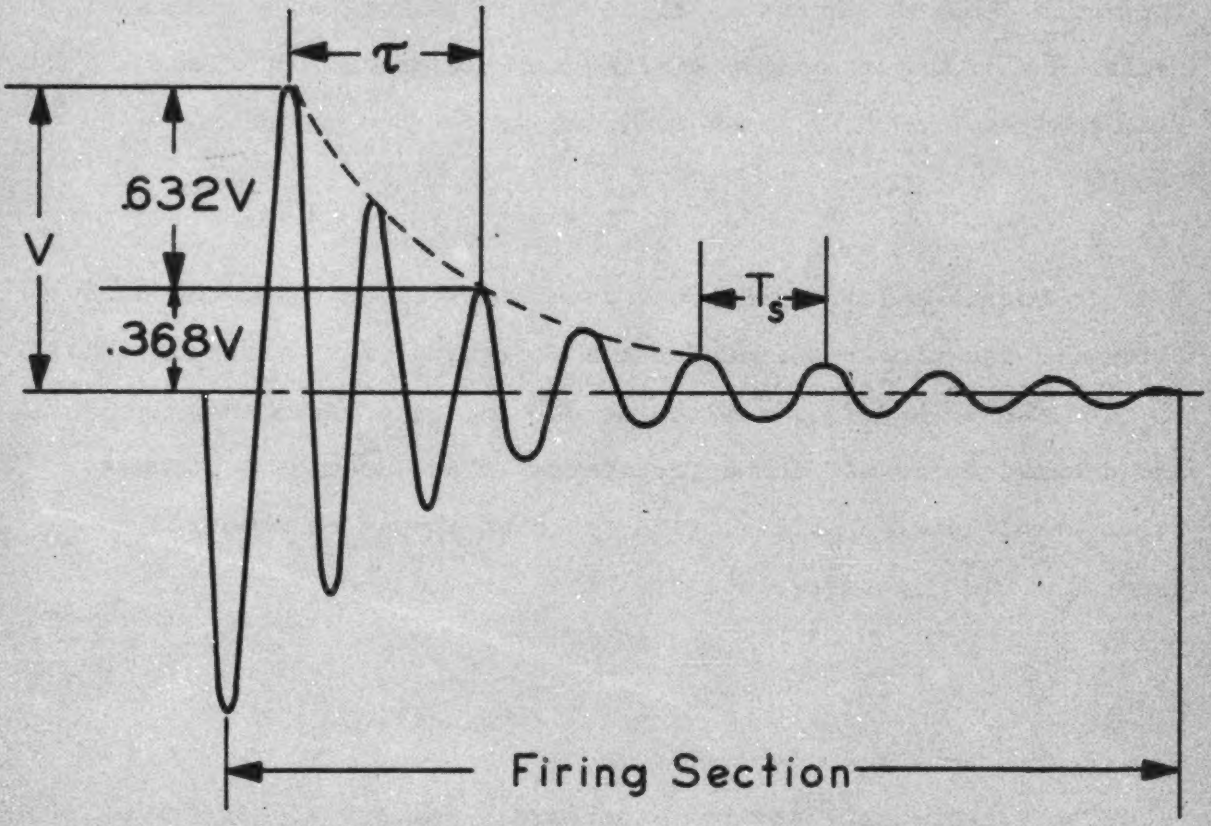

Figure 5

From the expanded waveform, determine the period of oscillation, T_S. A nominal value for the inductance of the secondary winding is $L_S = 65$ henries. Solve the following equation for the stray distributed capacitance C_D. Compute the "approximate" value for this distributed capacitance from the equation

$$T_S = 2\pi\sqrt{L_S C_D}.$$

When the period, T_S, is given in seconds and the inductance is given in henries, then the capacitance will be given in farads. The rapid decay of the oscillation is due to the large combined resistance of the secondary winding and the spark gap. The time constant for this decay is given as

$$\tau_d = \frac{2L_S}{R_G} .$$

To obtain a fair estimate of the time constant for the decay, determine the time required for the amplitude of the oscillations to decrease to 0.368 of its maximum value. Apply the above equation and determine the effective resistance of the secondary circuit. Use $L_S = 65$ henries and the time constant should be measured in seconds. The gap resistance will then be (in ohms):

$$R_G = \frac{2L_S}{\tau_d} .$$

The Intermediate Section

The intermediate section immediately follows the firing section, which is seen in Figure 3 as a series of gradually diminishing oscillations which disappear, or nearly disappear, before the points close again.

During this interval the breaker points are still open. The capacitor across the points prevents arcing and the capacitor absorbs some of the energy in the primary circuit by becoming charged. By the time the capacitor becomes fully charged, the points are open far enough to prevent arcing. After the firing oscillation of the secondary has ceased, the remaining energy stored in the capacitor discharges back and forth through the primary circuit, producing a diminishing oscillation. The period of that oscillation is determined essentially by the inductance of the primary winding L_p and the effective capacitance in the primary circuit. Measure the period of this oscillation, T_p, and compute the effective capacitance of the primary circuit by means of the equation:

$$T_p = 2\pi\sqrt{L_p C}.$$

where C will be in farads if L_p is given in henries and T_p is seconds. Use the value of L_p obtained in the study of the Dwell section of this exercise.

VI. *OTHER PHYSICAL PRINCIPLES IMPORTANT TO THE IGNITION SYSTEM*

There are many other physical principles that are utilized in the automobile ignition system, but we shall not have time to examine them all in detail. One factor that should be noted is the polarity of the secondary coil. This coil is wound so that the induced secondary voltage is large and negative rather than positive. The center electrode of the spark plug is at a lower potential than the outer electrode which is grounded. By grounding in the ignition system, we mean attachment to the automobile frame, which provides a return path for the current. The reason for this polarity in the secondary circuit is to assure that the spark will be from the center electrode to the outer electrode.

It must be remembered that moving negative charges (electrons) make up the current, and they will tend to move from a lower potential to a higher potential. It is the difference in temperature between the electrodes that makes it desirable to have the spark jump from the center spark plug electrode. The outer electrode is considerably cooler than the center one because it is in direct contact with the engine block, and the engine block is being cooled by the water jacket. The higher temperature of the center electrode gives the electrons an additional energy which lessens the voltage requirements for a spark. The graph of Figure 19 illustrates this effect.

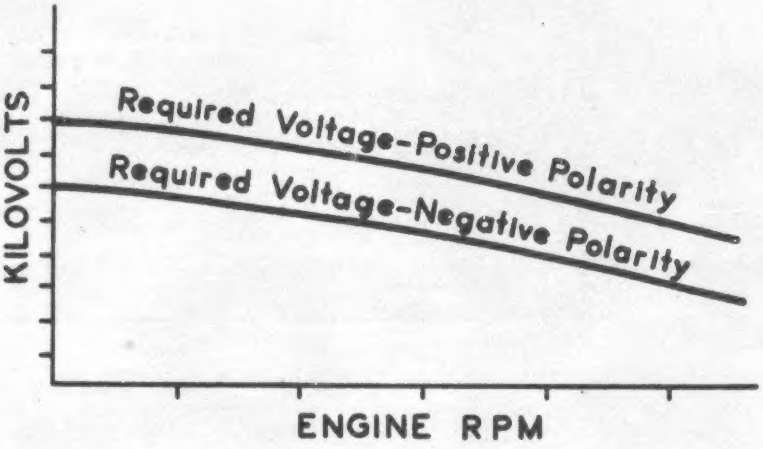

Figure 19

For best results, the center electrode of the spark plug should be flat and clean. This electrode is subject to a severe environment which may include high temperatures and sparking up to 300 times per minute. Under these conditions, wearing away of the spark plug electrode can occur even though it is made of wear-resistant nickel alloys. If the center electrode becomes pointed, it is much more difficult to produce a spark. As a matter of fact, the same principle is used in lightning rods, which are purposely made pointed on the end to reduce the chances for the rather more catastrophic spark of a lightning bolt. Of course, it is not impossible for a spark to jump from a pointed electrode, but it requires a higher voltage.

Question 14

Why is it more difficult to produce a spark if the center electrode of a spark plug becomes pointed?

We might also note the difference between standard spark plugs and resistor spark plugs. The two types are shown in a cutaway diagram in Figure 20.

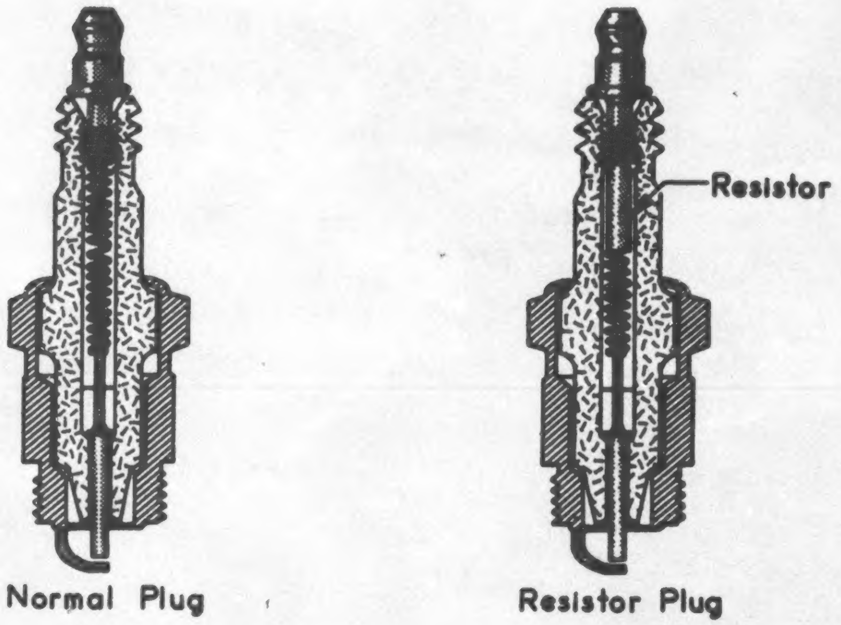
Resistor
Normal Plug
Resistor Plug

Figure 20

As can be seen from the figure, the resistor type is almost identical to the standard type, except for a 10,000 Ω resistance, between the spark plug terminal and the center electrode. This resistance will reduce the total current that flows through the plug, and so reduce the electrode wear. The secondary circuit oscillates like the primary circuit, which causes the spark to actually have several discharges. The spark plug resistance damps out this secondary oscillation more quickly but does not adversely affect ignition, since the very first surge through the spark plug is sufficient to ignite the fuel mixture. The graph of Figure 21 illustrates the effect of the resistor spark plug on the voltage in the secondary circuit.

Question 15

If the ballast resistor in the primary of an ignition system gets hot, what is the effect on the time constant of that circuit with the points closed?

Question 16

How does the use of resistor spark plugs affect the decay time of the oscillations in the secondary circuit of the ignition system when the points are open?

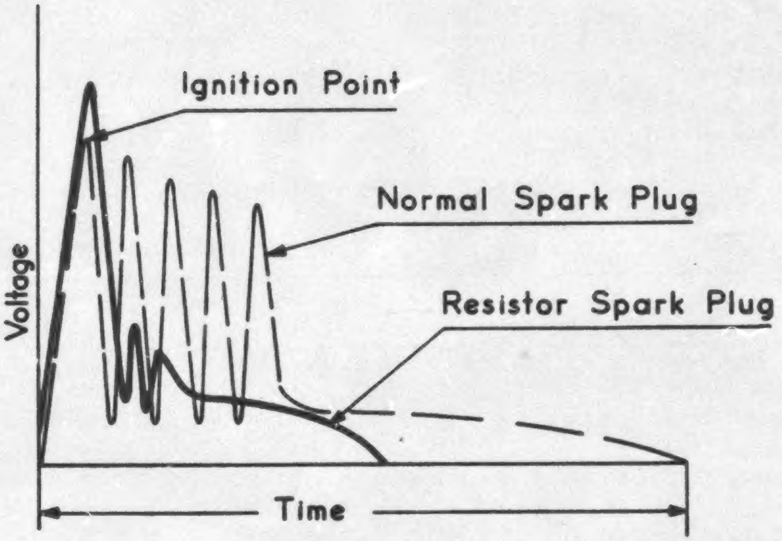

Figure 21

We have not yet discussed the important adjustments of dwell or timing. These factors are important for the proper operation of the automobile.

As you saw in Experiment 5, dwell refers to the cam angle for which the points remain closed. This concept is illustrated by Figure 22. The dwell can be increased by decreasing the gap. The dwell angle is directly related to the dwell time at any given engine speed. At high speeds, dwell time becomes critical, because it takes time for the primary current to build while the points remain closed.

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(You might want to turn back to Figure 12 to recall the kind of current-time relationship applicable to the period of dwell.) It is the magnetic field produced by the current in the primary that will be the source of spark energy after the points open again. If the dwell time is insufficient, the current will not have time to build adequately, the magnetic field will be smaller, and a weak spark voltage will be produced in the secondary windings as the field collapses after the points are opened.

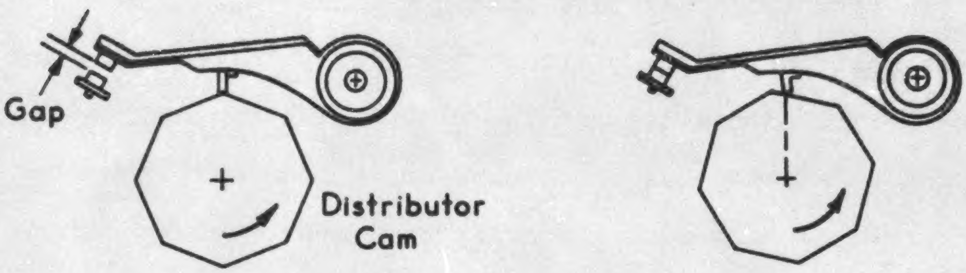
Another way of looking at this situation is that while the points are closed, the battery "pumps" energy into the coil which stores the energy as a magnetic field. When the points are opened, the secondary coil extracts the energy as the field collapses and passes the energy on to the cylinder in the form of a spark. If the dwell time is too short, the battery will not have time to pass enough energy, and the spark will be weak. By either way of looking at it, the conclusion is the same. The dwell, or gap, adjustment is important to high speed operation.

Question 17

How is the time constant in the primary of an ignition system affected when points are adjusted with too large of a dwell? Too small of a dwell?

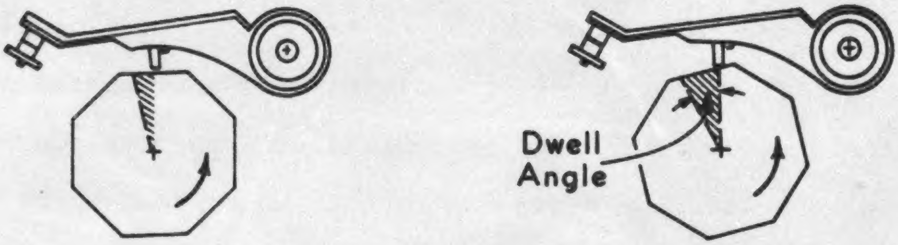
Question 18

Sketch, one below the other, graphs of voltage across the ballast resistor for a complete ignition system cycle for (a) dwell too large, (b) dwell too small, and (c) correct dwell. These graphs should be for the same engine speed.


Gap
Distributor Cam

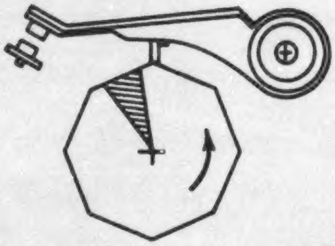
1) POINTS WIDE OPEN

2) POINTS CLOSE


Dwell Angle

3) POINTS REMAIN CLOSED

4) POINTS BEGIN TO OPEN



5) POINTS WIDE OPEN

DWELL IS THE CAM ANGLE THROUGH WHICH THE POINTS ARE CLOSED.

Figure 22

Spark advance is another aspect of good ignition system performance. The timing of the spark in the cylinder has to be adjusted to the position of the piston. In order to have combustion completed by a certain position of the piston past top dead center, the spark must be advanced as the engine speed increases. One way of advancing the spark is with a centrifugal advance mechanism. In this mechanism, two spring-mounted weights on the distributor shaft swing outward at higher engine speeds. The outward or centrifugal motion of the weights by means of a linkage rotates the cam assembly ahead of the distributor shaft rotation, causing the cam to open and close the breaker points earlier in the engine cycle.

Vacuum advance is another aspect of ignition system operation. When the engine is operating under a closed or nearly closed throttle, the density of the fuel-air mixture in the cylinders is lower. This lower density slows the rate at which fuel burns in the cylinders. Therefore, the spark must occur sooner to allow the completion of combustion at a favorable piston position. The vacuum advance operates off the manifold vacuum of the engine. The advance consists of a diaphram which is flexed by the manifold vacuum. In flexing, it turns parts of the distributor in a manner which advances the spark. By advancing the spark with vacuum and engine speed, more uniformly good performance over the full range of engine operation is achieved. For pollution control, spark advance is now being influenced by vehicle speed and air temperature. The devices used to perform such controls are getting more involved as engine development progresses. Eventually the problem of providing sufficient spark voltage for all engine speeds and operating conditions in such a way that performance and service life are maximized, while pollution is minimized, will be solved by using transistorized, or solid state ignition systems. More variations are possible electronically. Such systems are already used on some automobiles.

POST-TEST

THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

POST-TEST

THE PHYSICS OF THE AUTOMOBILE IGNITION SYSTEM

1. The primary of an ignition system coil has a resistance of 1.4 Ω and the ballast resistor in that circuit has a resistance of 1.6 Ω. With a 12-volt battery in the circuit, and the points closed, what is the maximum current?

   A. 36 A
   B. 8.6 A
   C. 7.5 A
   D. 4.0 A
   E. 19.2 A

2. A ballast resistor in the primary of an ignition system has a resistance of 2.80 Ω at 500 RPM when its temperature is 80°C. When immersed in ice water (at 0°C), the resistor has a value of 2.00 Ω. What is the temperature coefficient of resistance for the ballast resistor?

   A. $5.0 \times 10^{-3}/C^{o}$
   B. $4.5 \times 10^{-3}/C^{o}$
   C. $4.0 \times 10^{-3}/C^{o}$
   D. $3.5 \times 10^{-3}/C^{o}$
   E. $3.0 \times 10^{-3}/C^{o}$

3. A wire 10 cm long is placed in a magnetic field so that the length of the wire is at right angles to the field. When there is a current of 10 A in the wire, there is a magnetic force of 0.42 N exerted on the wire. What is the magnetic field, B?

   A. 1.27 T
   B. 1.21 T
   C. 0.48 T
   D. 0.61 T
   E. 0.42 T

4. A coil of wire produces an average magnetic field of 0.5 T inside of it when the coil carries a current of 8 A. The cross-sectional area of the coil is 4×10^{-4} m^2. What magnetic flux links the coil turns?

   A. 32×10^{-4} Wb
   B. 2×10^{-4} Wb
   C. 4×10^{-4} Wb
   D. 4 Wb
   E. 0.4 Wb

5. A 200 turn coil has a flux of 8×10^{-5} Wb linking it while the coil carries a current of 3 A. If the current (and therefore the flux) falls to zero in 0.01 seconds, what potential difference is induced across the ends of the coil?

   A. 24 V

   B. 8×10^{-3} V

   C. 16 V

   D. 1.6 V

   E. 0.03 V

6. The primary of an ignition coil has an inductance of 70 mH. If the current increases from zero to 3.5 A in 10 ms, what voltage is induced in the coil?

   A. -24.5 V

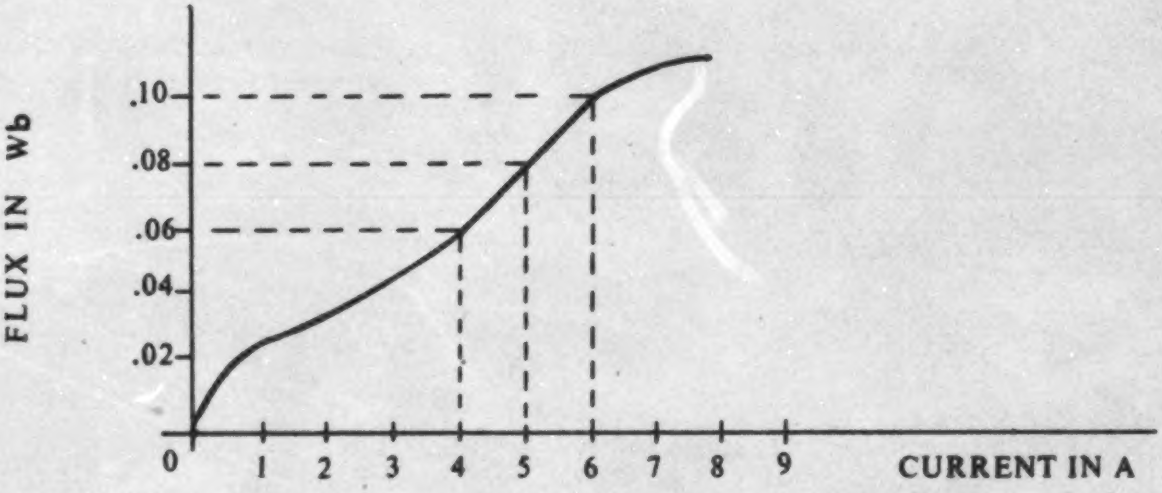
   B. -24,500 V

   C. +24.5 V

   D. +24,500 V

   E. -3500 V

7. The graph below is that of total flux linking a coil versus current. What is the inductance when the current is 5.00 A?



   A. 47 mH

   B. 200 mH

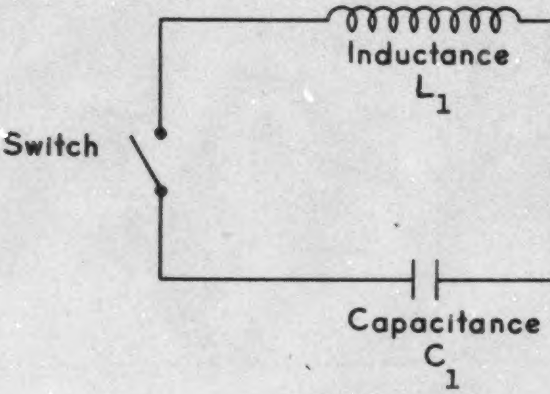
   C. 100 mH

   D. 10.0 mH

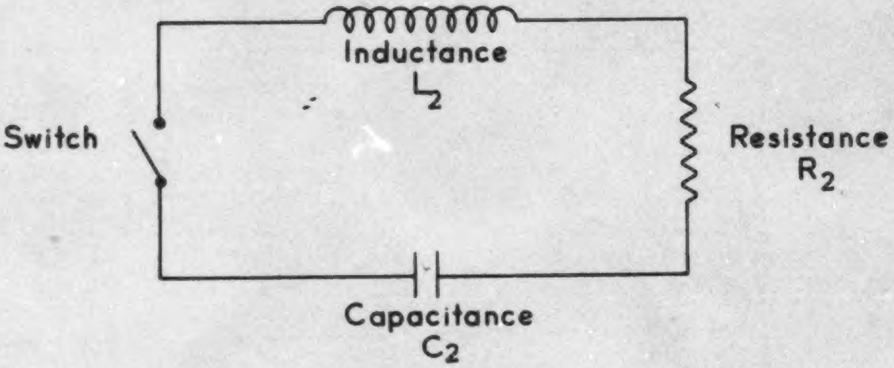
   E. 20.0 mH

Questions 8 - 13

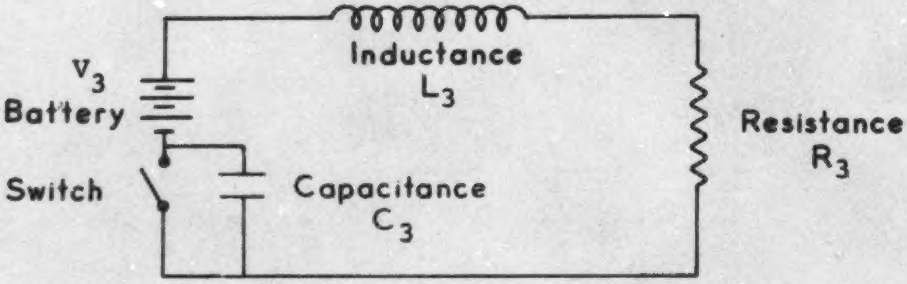
Each of the circuits below has a switch which can be open or closed. Each of the graphs represents current as a function of time.


Inductance
L_1
Switch
Capacitance
C_1

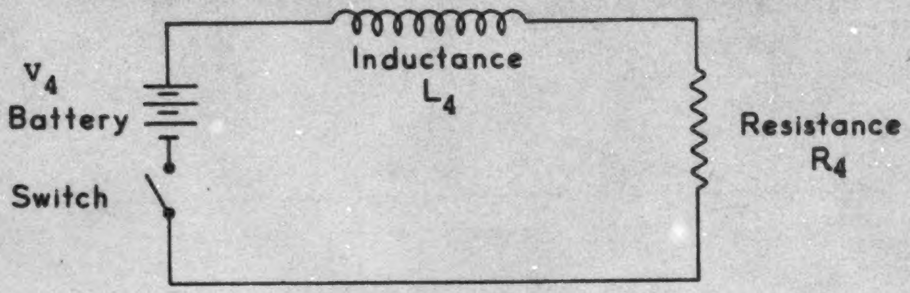
Circuit I


Inductance
L_2
Switch
Resistance
R_2
Capacitance
C_2

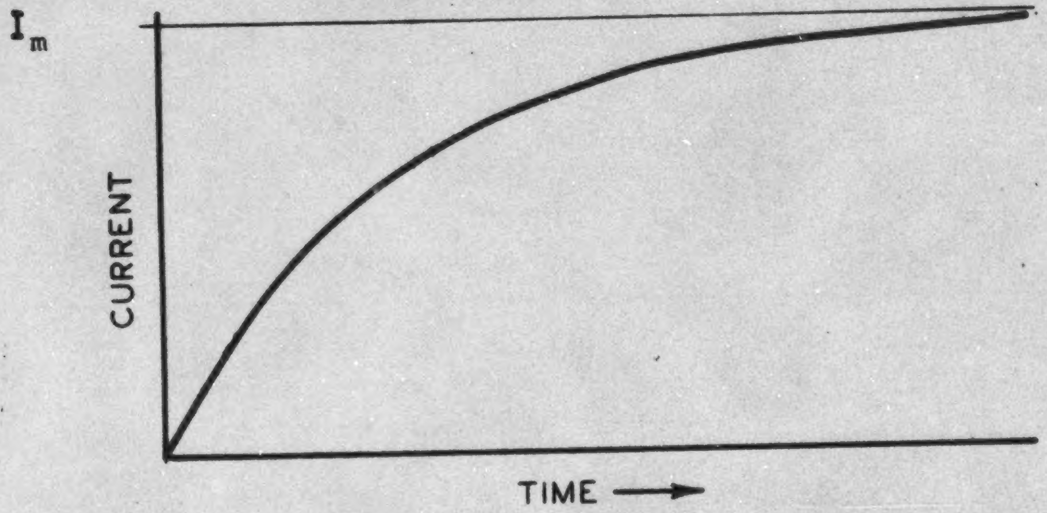
Circuit II


V_3
Battery
Inductance
L_3
Resistance
R_3
Switch
Capacitance
C_3

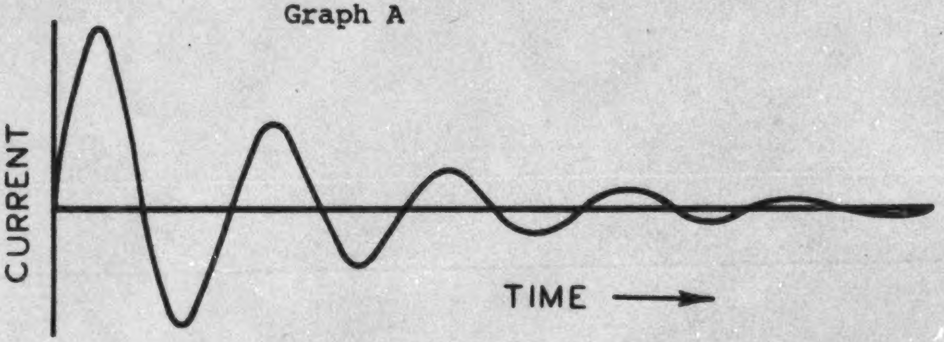
Circuit III


V_4
Battery
Switch
Inductance
L_4
Resistance
R_4

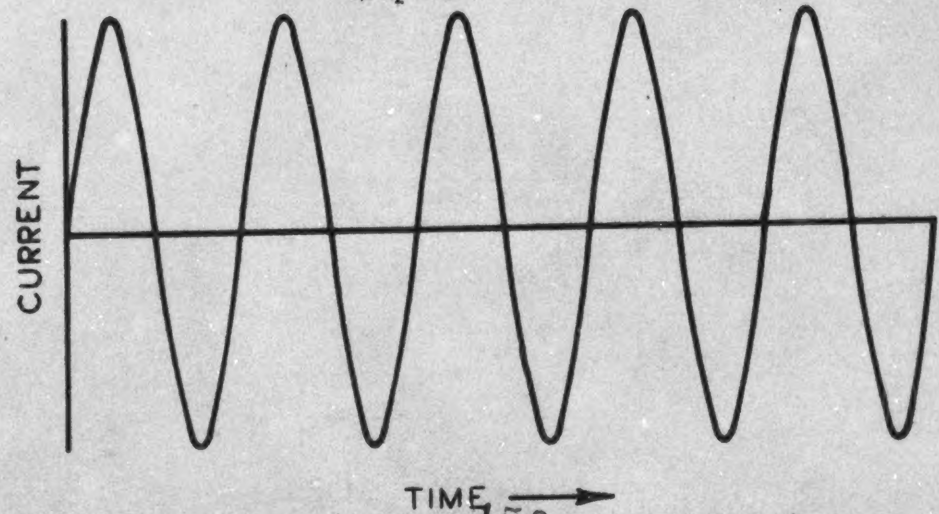
Circuit IV



Graph A



Graph B



Graph C

8. Assuming that C_1 and C_2 are initially charged and that C_3 is initially uncharged, which circuit or circuits would produce graph A when all switches are closed?

   A. I only
   B. II only
   C. III only
   D. IV only
   E. III and IV

9. Assuming that C_1 and C_2 are intially charged and that C_3 is initially uncharged, which circuit or circuits produce graph B when all switches are closed?

   A. I only
   B. II only
   C. III only
   D. IV only
   E. I and II

10. Assuming that C_1 and C_2 and C_3 are initially charged, which circuit or circuits produce graph C when all switches are closed?

   A. I only
   B. II only
   C. III only
   D. IV only
   E. I and II

11. Suppose $L_1 = L_2 = L_3 = L_4 = 50$ mH, $C_1 = C_2 = C_3 = 2 \times 10^{-7}$ F, $R_2 = R_3 = R_4 = 5\ \Omega$, and $V_3 = V_4 = 12$ V. Suppose C_1 and C_2 are initially charged and C_3 initially uncharged. When all switches are closed, what time constant, or period, or both is(are) characteristic of circuit I and what is(are) its(their) value(s)?

   A. 6.28×10^{-4}s period and 10^{-2}s time constant
   B. 3.14×10^{-3}s period
   C. 6.28×10^{-4}s period
   D. 6.28×10^{-4}s period and 5×10^{-3}s time constant
   E. 10^{-2}s time constant

12. Using the values and conditions specified in problem 11, what time constant, or period, or both is(are) characteristic of circuit II, and what is(are) its(their) value(s)?

A. 6.28×10^{-4}s period and 2×10^{-2}s time constant

B. 3.14×10^{-3}s period

C. 6.28×10^{-4}s period

D. 6.28×10^{-4}s period and 5×10^{-3}s time constant

E. 10^{-2}s time constant

13. Using the values and conditions specified in problem 11, what time constant, or period, or both, is(are) characteristic of circuit IV, and what is(are) its(their) value(s)?

A. 6.28×10^{-4}s period and 10^{-2}s time constant

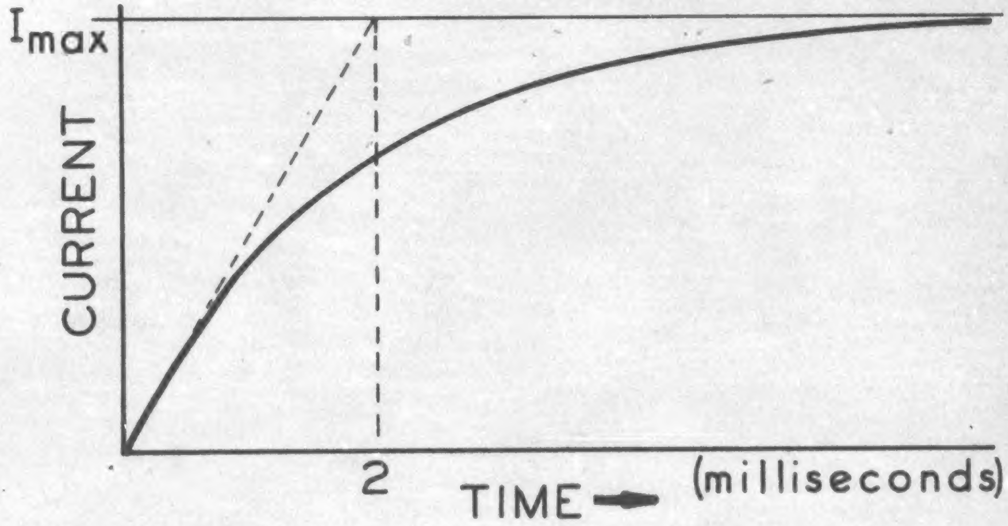
B. 3.14×10^{-3}s period

C. 6.28×10^{-4}s period

D. 6.28×10^{-4}s period and 5×10^{-3}s time constant

E. 10^{-2}s time constant

14. The graph below shows the current in the primary of an ignition system as a function of time while the points are closed. If the resistance of the primary circuit is $3\ \Omega$, what is the value of the inductance of the primary coil?



A. 6.0 mH

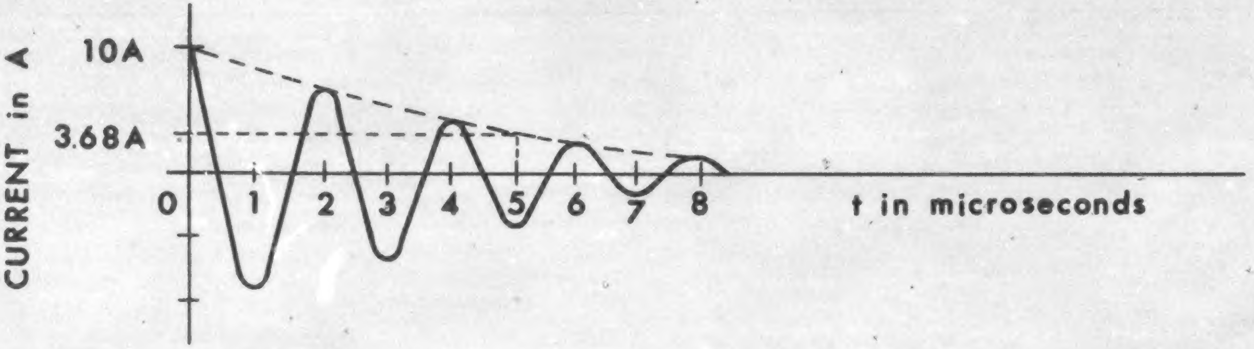
B. 6.0 H

C. 6000 H

D. 3 mH

E. 3.0 H

15. The graph below shows the current in a circuit as a function of time. The circuit has an inductor, capacitor, and resistor in series. If the capacitance has a value of 5×10^{-12} F, what is the value of the inductance?



A. 30 mH

B. 20 mH

C. 40 mH

D. 4 mH

E. 2 mH

16. Suppose the inductance of the circuit of problem 15 were 50 mH. What would have been the resistance of the circuit?

A. 10,000 Ω

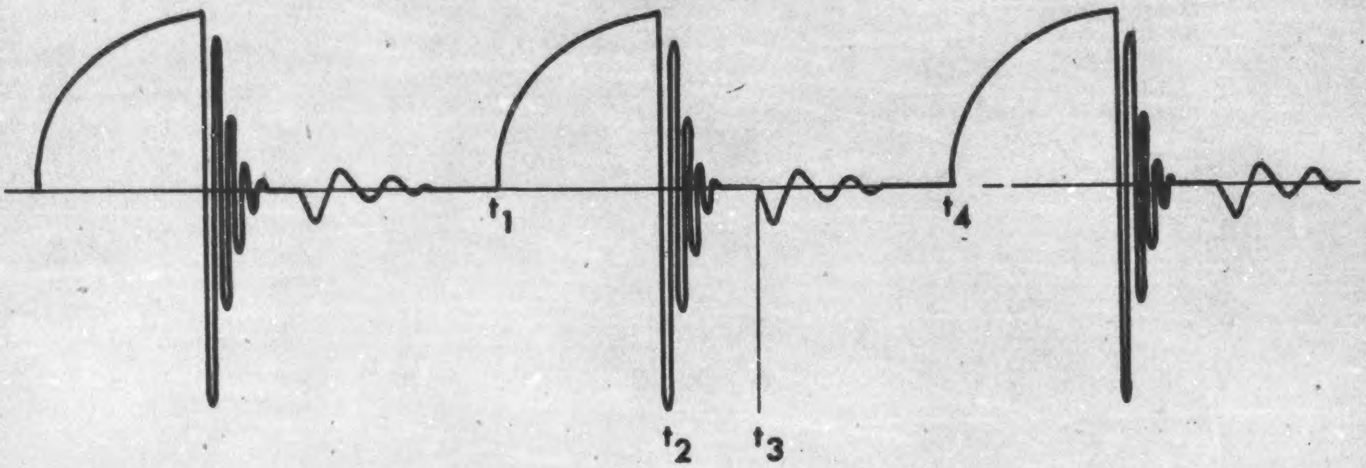
B. 20,000 Ω

C. 2,000 Ω

D. 1,000 Ω

E. 5,000 Ω

17 - 20 The graph below shows the current in the primary of an ignition system as a function of time.



17. When do the points open?

    A. at time t_1

    B. at time t_2

    C. at time t_3

    D. at time t_4

    E. Between time t_1 and t_2

18. How long are the points closed?

    A. t_1

    B. t_2

    C. t_3 minus t_2

    D. t_4 minus t_2

    E. t_2 minus t_1

19. How long are the points open?

    A. t_1

    B. t_2

    C. t_3 minus t_2

    D. t_4 minus t_2

    E. t_2 minus t_1

20. How long is the spark plug firing?

    A. t_1

    B. t_2

    C. t_3 minus t_2

    D. t_4 minus t_2

    E. t_2 minus t_1

GLOSSARY OF EQUATIONS AND SYMBOLS

$V = IR$

$R = R_o(1+\alpha T)$

$B = \frac{F}{I\ell}$

$V = \frac{W}{Q}$

$I = \frac{Q}{t}$

$\Phi = BA$

$E = N\frac{\Delta\Phi}{\Delta t}$

$E = -L\frac{\Delta I}{\Delta t}$

$T = 2\pi\sqrt{LC}$

$L = \Delta\Phi_{total}/\Delta I$

$\tau_{LR} = L/R$

$\tau_{decay} = 2L/R$

$Q = CV$

V: Potential difference in volts

E: Induced EMF in volts

N: number of turns

F: force in newtons

Φ: flux in webers

Φ_{total}: total flux linking a circuit, in webers

t: time in seconds

L: inductance in henries

I: current in amperes

Q: charge in coulombs

C: capacitance in farads

T: temperature in ^{o}C in $\left[R_o(1+\alpha T)\right]$

T: time in seconds in $T = 2\pi\sqrt{LC}$

τ_{LR}: time in seconds

τ_{decay}: time in seconds

W: work in joules

ℓ: length in meters

A: cross-sectional area in m^2

B: magnetic field in N/A-m

R: resistance in ohms